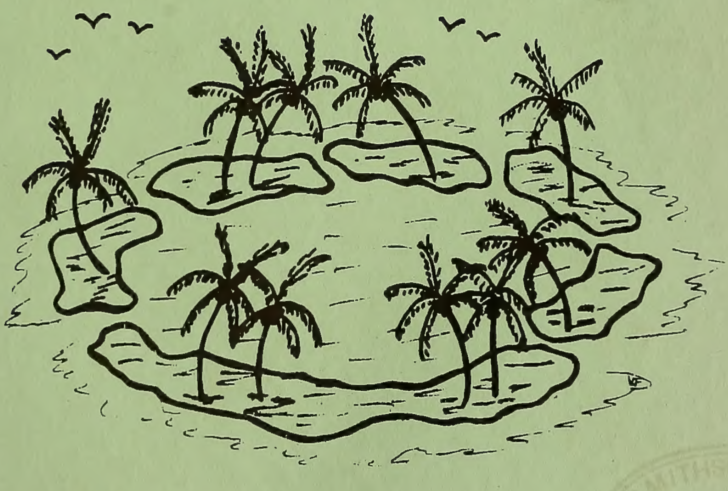
No. 95 May 15, 1963

ATOLL RESEARCH BULLETIN

Effects of Hurricane Hattie on the British Honduras Reefs and Cays, October 30-31, 1961

by

D. R. Stoddart



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THE PACIFIC SCIENCE BOARD
National Academy of Sciences—National Research Council
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ACKNOWLEDGMENT

It is a pleasure to commend the far-sighted policy of the Office of Naval Research, with its emphasis on basic research, as a result of which a grant has made possible the continuation of the Coral Atoll Program of the Pacific Science Board.

It is of interest to note, historically, that much of the fundamental information on atolls of the Pacific was gathered by the U. S. Navy's South Pacific Exploring Expedition, over one hundred years ago, under the command of Captain Charles Wilkes. The continuing nature of such scientific interest by the Navy is shown by the support for the Pacific Science Board's research programs during the past fifteen years.

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PREFACE

Hurricane Hattie passed across the British Honduras coast on October 30-31, 1961, and this paper presents in some detail the effects of the storm on coral reefs and particularly on reef islands in its track. I am much indebted to the Royal Society of London for supporting the re-survey expedition, which lasted from February to May 1962: and also to Miss Evelyn L. Pruitt, Head, Geography Branch, Office of Naval Research, Department of the Navy, Washington, who arranged trans-atlantic transportation for me. Without this great assistance, this investigation would not have taken place. Much of this report necessarily deals with pre-hurricane conditions - in outline only for the atolls (Turneffe, Lighthouse and Glover's Reefs) which have been described in a previous paper (Stoddart, 1962b), in greater detail for the hitherto undescribed cays of the barrier reef. This material was gathered during two earlier expeditions: The Cambridge Expedition to British Honduras 1959-60, led by J.E. Thorpe, and an expedition in 1961 sponsored by the Coastal Studies Institute, Louisiana State University, and the Office of Naval Research, Washington. I am most grateful to my companions on the first expedition; and to Professor R.J. Russell and Miss E.L. Pruitt for their great help on the second. A special word of thanks must go to my assistants, Mr. J.D. Poxon and Mr. Stephen P. Murray, for their aid. On all these expeditions, my plant collections have been identified by Dr. F.R. Fosberg; to Dr. Fosberg, and to Dr. M.H. Sachet, both of the Pacific Vegetation Project, go my very best thanks, not only for this, but for many other kindnesses. This whole project has been carried out under the direction of Professor J.A. Steers, of Cambridge, who has given encouragement and advice at all stages; I trust his influence may be seen in the following pages. Since 1959 I have been supported by funds from the Department of Scientific and Industrial Research, London, held at the Department of Geography, Cambridge, England.

One is embarrassed by the numbers of people who have so freely given their help during these investigations, especially after the hurricane, when most had more to occupy their minds than wandering geomorphologists. I must thank in particular Sir C.H. Thornley and Sir P.G.H. Stallard, successively Governors of British Honduras, for very practical assistance, and the Government of the Colony for customs exemption and other favours; my good friends Dr. and Mrs. Stuart Heap and Mr. and Mrs. Norman Stalker, for their unflagging hospitality; Mrs. Olivia C. Stuart, who both before and after the hurricane welcomed me to her home at no small personal inconvenience; and Belize Estate and Produce Company Limited and the Harrison Line for invaluable help with shipping stores and specimens. My thanks also to the local fishermen who have at one time or another taken me from cay to cay: especially Mr. Philip Young in the Ramrod in 1961, and Mr. Pete Young in the Sunshine and Mr. Maurice Miller in the Joy in 1962. I am grateful also to Government Departments in British Honduras who gave assistance, notably the Forestry Department, Survey and Lands Department, Information Department, Customs Department and British Honduras Broadcasting Service; and in England especially to the Hydrographic Department, Admiralty, under Admiral E.G. Irving, O.B.E. R.N., the British Museum (Natural History), and the Royal Geographical Society. The Coastal Studies Institute of Louisiana State University helped with the loan of instruments. Many persons have given freely of their knowledge and advice, including Dr. Adrian

Richards, Office of Naval Research, London; Dr. Gordon E. Dunn, U.S. Weather Bureau, Miami; Dr. Michael Mancoo, Palisadoes Airport, Jamaica; Captain W.S. Eustace, Master, m.v. Tactician; Mr. M.S. Porcher, Chief Secretary, British Honduras; Colonel Fairweather, British Honduras Volunteer Guard; and Colonel Charnock Wilson, Lately of the British Honduras Coconut Marketing Board. Figure 5 is reproduced by courtesy of the U.S. Weather Bureau; and Figures 2 and 3 are based on information supplied by Dr. Gordon E. Dunn. Figures 23 and 33 are based on Admiralty charts, by permission of Admiral Irving; Figure 14 on the air photographs taken by the R.A.F. in 1962, loaned by Admiral Irving; and Figures 15, 16 and 34 on United States Navy photographs of 1945, supplied by Coastal Studies Institute.

There are inevitably many other persons and organisations I ought to mention; my appreciation is by no means lessened by my inability to name them all here. Perhaps my thanks can best be phrased in the words of one of the first English students of the corals, John Ellis, who in 1755 wrote as follows:

> "Many hints I owe to the conversations of my Friends; and I cannot but acknowledge, that whatever else may have accrued to me from these Pursuits, they, at least, have been the Means of procuring me many valuable Friendships, and an Acquaintance with Men who do Honour to their Country, and their Species."
> (Ellis, 1755, 100).

1. INTRODUCTION

The effect of hurricanes and catastrophic storms on reefs and reef islands has long been appreciated - Charles Darwin cited numerous examples in his "Structure and Distribution of Coral Reefs" (1842, 95-97) - and the literature on reefs is scattered with abundant references to such effects. Wells (1951, 5-7) for example, has catalogued the tremendous morphologic changes resulting from the 1905 and 1918 typhoons at Arno Atoll, Marshall Islands. Yet the fact remains that very few studies have been made of hurricane effects either during or soon after their occurrence. For many years the only such study was Moorhouse's report on the effects of the 1934 cyclone at Low Isles, Great Barrier Reef of Australia (Moorhouse, 1936), and the subsequent comments by Steers (1937) and Fairbridge and Teichert (1948, 75-83). The work at Low Isles has been continued with the excellent report by Stephenson, Endean and Bennett (1958) on the effect on the corals themselves of the 1954 cyclone. In recent years, there has been a great increase in interest in the physiographic, geologic, botanical, biological and human effects of severe storm action, largely as a result of Typhoon Ophelia, which struck Jaluit Atoll, Marshall Islands, on January 7-8, 1958. Seven scientists studied the changes three and a half months after the passage of this storm, and their reports form the only detailed survey of severe storm effects on atoll land areas (Blumenstock, 1958; McKee, 1959; Blumenstock, editor, 1961). Nearly three years after the passage of Ophelia, Jaluit was revisited by a second party to investigate the modification of the hurricane-induced changes, and a preliminary report has already appeared (Blumenstock, Fosberg and Johnson, 1961). Further detailed investigations have also recently been carried out at Ulithi Atoll, Caroline Islands, struck by a typhoon, also named Ophelia, on 30 November, 1960; Blumenstock led a party to that atoll in January 1961, and a report is anticipated. Emery (1962, 59-61) has recently described typhoon effects on Guam.

Hurricane Hattie is of special interest in the study of catastrophic storms in reef areas. While long neglected, the reefs of British Honduras have recently seen increasing activity by a number of workers. Vermeer (1959) has published a general account of the whole reef area based on a reconnaissance study made in 1957. Dr. Edward G. Purdy, currently investigating barrier reef lagoon sediments, spent several seasons in the area before the hurricane, and has returned since. The present writer began work on the cays in December 1959, and in the course of two expeditions (December 1959 - June 1960; May - August 1961) completed mapping of some seventy reef islands, with comprehensive ground and air photo coverage, plant collection, and incidental reef observation. Accounts of part of this work have already appeared (Stoddart, 1960, 1962a, 1962b). The programme of mapping was completed less than three months before Hurricane Hattie struck the area on October 30-31, 1961. This afforded what is probably a unique opportunity to study in detail the effect of hurricanes on reef islands, on the basis of maps and other data obtained immediately before the hurricane struck. First reports indicated appalling devastation at the capital, Belize (e.g. Boga, 1961), and it was soon apparent that the hurricane must have

affected much of the northern barrier reef and probably Turneffe and Lighthouse Reefs also. With Royal Society support I was able to spend February-May 1962 in British Honduras: during this re-survey expedition I was able to fly over the whole length of the atoll and barrier reefs, re-photograph all the cays from the air, fly along the whole coastline of the country, and, in a number of sea trips, re-map cays in the devastated areas of the barrier reef, Turneffe Islands and Lighthouse Reef.

Description of the Reef Area

British Honduras is situated in the south-eastern part of the Yucatan Peninsula, Central American mainland. The southern part of the country consists of an upfaulted block of Palaeozoic metamorphosed sediments and igneous intrusions, rising to 3650 feet above sea level. South of these Maya Mountains is a lower-lying hilly area of Cretaceous and Eocene limestones, shales and sandstones; the limestones also overlap the western part of the Maya Mountains, and constitute the whole of the northern lowlands of British Honduras. The Yucatan Peninsula north of British Honduras is also built of low-lying limestones, previously thought to become younger northwards, but now shown by Butterlin and Bonet (1961) to exhibit a less regular pattern and to be mainly Eocene. Fault systems in the British Honduras highlands are dominantly east-west, and in the northern lowlands northeast-southwest (Ower, 1929; Flores, 1952; Dixon, 1956).

The greater part of the east coast of Yucatan is straight and featureless, apart from two mangrove-fringed embayments at Bahia Espiritu Santo and Bahia de la Ascension. Reef development along this coast appears to be poor (Edwards, 1957). South of the British Honduras border, however, the coastline becomes widely embayed and overlooks a broad but shallow coastal shelf, fringed on its outer edge by a barrier reef and cays. This reef extends with few breaks, following an arcuate course, for 130 nautical miles, to within 16 miles of the mainland Honduras coast at the foot of the peninsula. It encloses a lagoon, on the coastal shelf, which increases gradually in depth from 1-2 fathoms in Chetumal Bay to 25-30 fathoms at its southernmost extent. Cays on the barrier reef are of several types: on the barrier itself, sand and shingle islands have been built by wave refraction at many major reef gaps. Lagoonward from the barrier, a number of larger cays, with sandy seaward rims and mangrove swamp to leeward, rise from a "low platform" at 2-4 fathoms depth, which extends along the whole length of the shelf edge, and from which the present reefs rise. Clusters of mainly mangrove islands within the coastal lagoon are rather localised: one group lies south-east of Belize, at the inner end of a remarkable sinuous channel which intersects the barrier reef with depths of up to 33 fathoms; a second group is found in the central part of the lagoon, between Placencia village and the prominent Gladden Spit elbow; and a third group is found near the mainland coast between Punta Ycacos and Punta Gorda.

Outside the barrier reef the sea deepens rapidly - soundings of 4800 feet are found within 3½ miles of the southern barrier reef at

Ranguana Entrance. Three atolls rise to the surface from this deep water outside the barrier. Turneffe Islands, more properly a shallow, reef-fringed bank covered with much mangrove, has a number of small sand and shingle cays on its exposed eastern reefs. Lighthouse Reef, a true atoll with lagoon depths averaging 2-3 fathoms, lies 11-18 miles seawards from Turneffe Islands. Before the hurricane there were four small sand cays on this atoll, and two much larger sand and mangrove islands. Finally, the Glover's Reef atoll, with lagoon depths of up to 24 fathoms, lies south of Turneffe and Lighthouse Reefs; it has six sand and shingle cays on its south-east reef. All these atolls are elongated in a generally NNE-SSW direction, and are $30\frac{1}{2}$, 22 and 16 miles long respectively. All of them, too, appear to be bounded by steep slopes, especially on their east sides: thus there are soundings of up to 1100 fathoms within $3\frac{1}{2}$ miles of the east reefs of Lighthouse Reef. It seems quite probable that these gross features of the reefs are the result of coastal faulting, resulting in alignment of the reefs and pronounced submarine relief. The atolls are described in detail in my previous Bulletin (Stoddart, 1962b; hereafter referred to as ARB 87).

Maximum elevations of reef islands are greatest on the exposed cays of Lighthouse and Glover's Reefs: 10.5 feet before the hurricane at Half Moon Cay, Lighthouse Reef, and 9-10 feet at Long Cay, Glover's Reef. On the east reefs of Turneffe most of the sand cays are 3-5 feet high; shingle is present in lesser amounts than on the more exposed cays, and what is found is of finer calibre. On the sections of the barrier reef sheltered from the prevailing winds by the atolls the cays are wholly built of sand, lack protective shingle ridges, and rarely rise more than 3 feet above the sea. Along the southern barrier reef, not protected by the atolls, shingle ridges are found, rising 5-6 feet above sea level (Stoddart, 1962a).

Climatic data for this area are meagre in the extreme, and the only long-term records available are for the coastal capital, Belize (Wallace and Spano, 1962); the most recent survey of mainland climate is by Romney and others (1959, 15-22). Rainfall increases on the mainland from less than 20 inches on the north coast of Yucatan to more than 170 inches on the southern coastal lowlands of British Honduras, and to probably over 200 inches on the Maya Mountains. Belize itself has an average of 69.6 inches. On the barrier reef, conditions probably reflect the coastal pattern: Ambergris Cay in the far north probably has 50-60 inches per annum; the southernmost barrier reef cays may exceed 80-90 inches. The three atolls may have about 70 inches per annum. Most rainfall falls from June to December, with heaviest monthly totals in September and October, and a pronounced dry season from March to May. Variability from year to year is considerable. Winds are dominantly easterly, except for short periods in winter, when cold "northers" reach the area from North America. Temperatures are high, with mean maximum monthly temperatures at Belize varying from 81-88°F and mean minimum monthly temperatures from 68-75°. The highest temperatures are experienced from April to September. At Rendezvous Cay, barrier reef, mid-day temperatures from September 1959 to May 1960 ranged from 79 to 89°.

The main coastal current flows from the south-east, from Cabo Gracias á Dios northwards to the Yucatan Channel. However, British Honduras waters experience a counter-current, flowing anti-clockwise in the Gulf of Honduras, giving predominantly southerly water movements over most of the coastal shelf, sometimes extending out to the atolls, depending to a considerable extent on local wind conditions. Mean monthly sea temperatures at Rendezvous Cay ranged from 26.5 to 29.8°C, September 1959 to May 1960. Tides are less than 2 feet throughout the area, and local movements of sea level may reflect wind influence to a greater extent than purely tidal movements.

Apart from villages on Ambergris Cay and Cay Caulker, barrier reef, each with about 300 inhabitants, the population of the reef islands is restricted to a semi-permanent lighthouse staff on certain cays, and a number of temporary residents, mainly fishermen and coconut workers. On the three atolls, for example, before the hurricane, there were seven settlements on Turneffe (two associated with lighthouses), four on Lighthouse Reef (two of them associated with lighthouses), and three on Glover's Reef. The total population of the atolls probably never exceeded 50 persons. On the barrier reef, apart from lighthouse stations and the two villages, only a dozen or so cays were occupied, and the majority had no permanent houses and were visited infrequently. Most of the temporary visitors had permanent homes in Belize or the coastal settlements, chiefly Stann Creek, Mullins River, Monkey River and Placencia. The greatest temporary increase in population occurred during public holidays at St. George's Cay, with about 40 houses, used as a holiday resort by people from Belize.

For charts of the atolls, reference should be made to Figures 14, 27 and 37 in ARB 87. Detailed surveys of various dates provide the basis for excellent Admiralty charts of the barrier reef lagoon. See particularly Admiralty charts:

522. Belize Harbour (1957-1958)

959. Approaches to Belize (1921-1922)

1204. West Indies from Belize to Cabo Catoche (1830-1837)

1573. Honduras Gulf (1835-1841)

1797. Ranguana Cay to Columbus Cay (1830-1841)

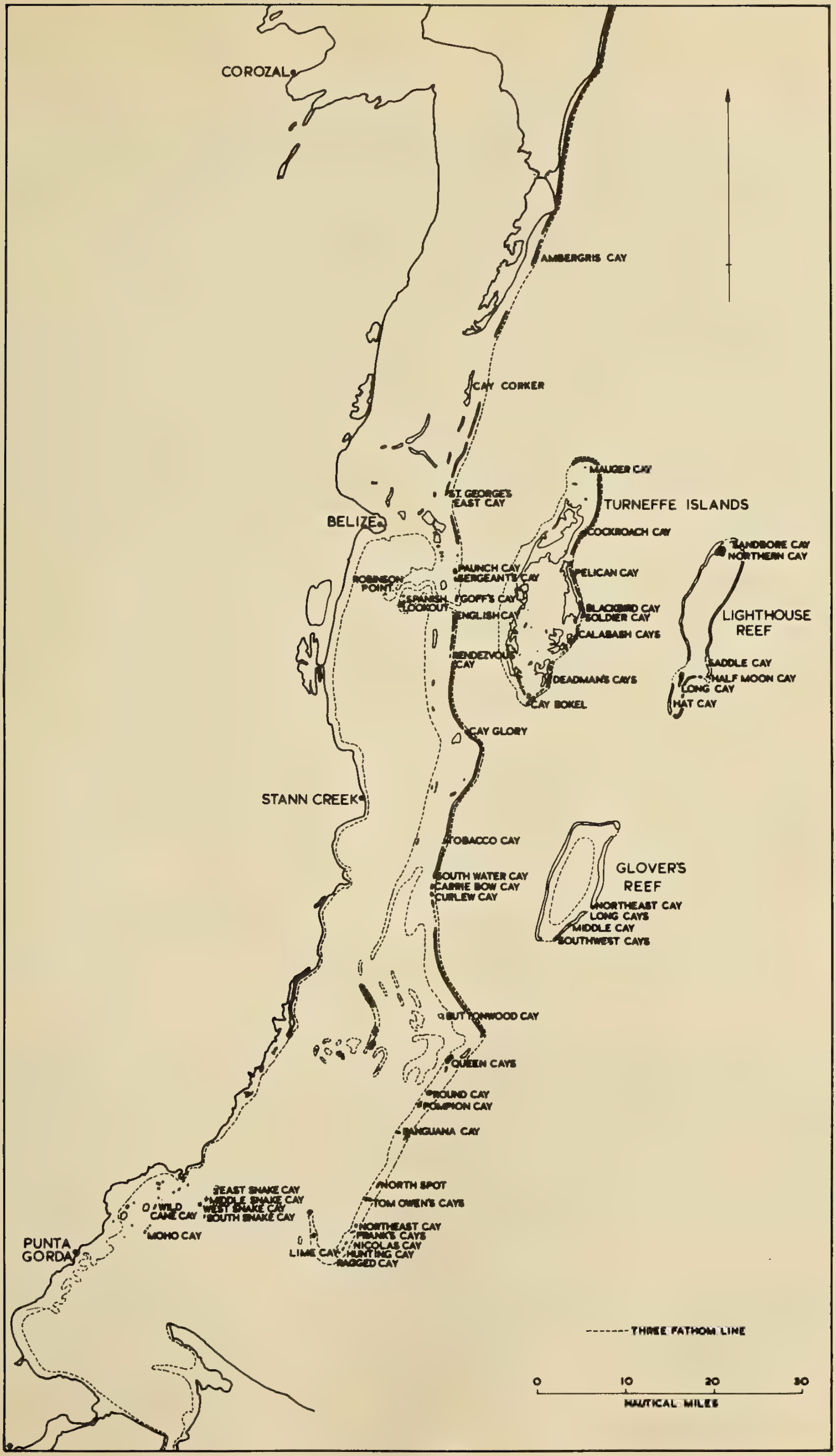


FIG. 1 – LOCATION OF BRITISH HONDURAS CAYS

II. HURRICANE HATTIE

Hurricane Hattie has been the most important storm to affect the reefs and cays of British Honduras for many years. It is comparable in intensity to Hurricane Janet of 1955, which, however, passed to the north of the main reef area and devastated Corozal and Chetumal (Pagney, 1957). Storms of similar magnitude have occurred in 1945 in Toledo District; in 1931, causing great damage and loss of life at Belize (Cain, 1933); and in 1787, when Belize was almost completely destroyed. Details of these and other earlier hurricanes are given in Appendix 1. Hattie achieved its main notoriety for the great damage it inflicted to life and property in the coastal settlements. Much of Belize and Stann Creek were badly damaged, though not beyond the possibilities of repair, and some smaller villages were almost entirely wiped out. Damage at Belize was so considerable that tentative plans were made for the re-location of the capital at Roaring Creek, 50 miles inland, and the extent of property damage has been roughly estimated at £20 m.* (Rickards, 1962). Of the approximate total of 250-260 deaths, most occurred in the larger coastal settlements: 94 in Belize City, 60 in Stann Creek Town, and 46 in Mullins River, according to the official list. Numbers of deaths on the cays are in the nature of things difficult to determine, but the following list, based on the official list, gives a close approximation; additions have been made on the basis of information collected during the 1962 expedition.

Table 1. Mortality on Cays during Hurricane Hattie

Barrier Reef:	Cay Caulker	14
	Rendezvous Cay	2
Turneffe Islands:	Berry Cays	3
	Soldier Cays	7
	Cay Bokel	6
	Calabash Cays	10
	Bull Bay	1
Lighthouse Reef:	Northern Cay	1
	Long Cay	1
Total:		45

It is said that no person who survived the actual storm subsequently succumbed to disease or other cause contingent on the hurricane, largely as a result of the efforts of United States and British military forces. However, persons were found up to 13 days after the storm stranded on cays, particularly on the Turneffe lagoon mangroves, and some died soon after rescue. It is quite possible that others survived for a period of days and died before being found. Similarly, it is not possible to be certain that all persons in the reef areas have been accounted for.

It is not the purpose of this chapter to discuss the meteorology of Hurricane Hattie, or the reasons for its unusual westward recurvature on 29-30 October. For discussions of the purely meteorological aspects, see Dunn and others (1962) and Nancoo (1962**). This chapter sets out to record as accurately as possible changing wind and wave conditions

* $ 33,600,000

** Nancoo, M.E. 1962. Hurricane 'Hattie'. Weather 17: 295-304.

during the passage of Hurricane Hattie, as a necessary preliminary to understanding the resulting changes on reefs and cays. The first part is based on meteorological information collected by the U.S. Weather Bureau (U.S. Weather Bureau, 1962); the second on information gathered at numerous localities in British Honduras.

Development of Hurricane Hattie

Hurricane Hattie was first identified as a tropical storm at Lat. 12.9°N, Long. 82.4°W, near San Andres Island, off the east coast of Nicaragua, during the afternoon of 27 October 1961. The disturbance followed an afternoon of light winds on the morning of the 27th and on the previous afternoon. The first advisory for the tropical storm was issued at 1600 h Belize time, 27 October, at about the time that Hattie passed close to San Andres (all times in this report, except where otherwise stated, are correct for Belize; add 1 hour to convert to Eastern Standard Time, and 6 hours to convert to Greenwich Mean Time). Steady winds of 70 knots were experienced at San Andres, gusting to 90 knots, with a minimum pressure at 0800 h, 28 October, of 991 mb. At this time gale force winds extended 125 miles to the north and 60 miles to the south of the storm centre, which was moving slowly northwestwards at about 8 mph. Northerly movement is usual with hurricanes originating in the San Andres area, and Hattie continued along this course on 28 and 29 October, at 6-7 mph. During the morning of 28 October (1000 h), the storm intensified: minimum pressure reported by aircraft penetration fell to 28.62 in (969 mb), with hurricane force winds extending 40 miles from the centre at 13.9°N, 81.6°W, maximum winds near the centre of 125 mph. and gale force winds extending 140 miles to the NE and 70 miles to the SW. Minimum pressure fell during the afternoon to 28.23 in (956 mb) at 1600 h, and gale force winds extended for 150 miles in all quadrants. During the night the hurricane continued to intensify, pressure falling to 28.11 in (952 mb) at 2200 h, 28 October. The following morning the storm continued to move northwards at about 9 mph; at 1000 h, 29 October, gale force winds extended for 185 miles in the eastern and 140 miles in the western semi-circle from the centre, now at 17.4°N, 81.3°W. Advisory 8 issued by the Miami Weather Bureau at this time warned of destructive winds and high tides in the Cayman Islands and Cuba.

During 29 October, however, Hurricane Hattie began to move toward the northwest at a slightly faster rate (13 mph). Reconnaissance aircraft reported wind speeds of 128 mph in the northern sector and 113 mph in the southern sector at 5000 ft. By 1600 h, gale force winds extended for 200 miles northeast of the centre and for 140 miles southwest. When the storm reached within 100 miles of Grand Cayman Island, however, the rate of forward movement decreased sharply, and late on the 29th and early on the 30th October, Hattie began to move slowly towards the Yucatan Peninsula. At 0100 h, 30 October, gale force winds extended 200 miles to the northeast and 140 miles to the southwest of the storm centre, but winds at both Grand Cayman and Swan Islands remained below hurricane force as Hattie passed between them.

In the early hours of 30 October, Hattie entered its third phase, moving westward at the rapid rate of 12-15 mph, and intensifying, with central pressure falling to 27.82 in (942 mb) at 0400 h. Advisory 11,

issued at this time, was the first to warn of high winds and tides along the east coast of the Yucatan Peninsula. Advisory 12, at 1000 h, 30 October, estimated storm tides at 15 feet above normal where the centre reached the coast, probably between Belize and Chetumal, Quintana Roo. Minimum pressure was now down to 27.29 in (924 mb); gales extended 230 miles to the NE and 140 miles to the SW. An intermediate bulletin from Miami stated that "During the forenoon Swan Island has been experiencing winds of 50 to 60 mph, with gusts of 60 and 70 mph. Waves 20 to 25 feet high have been lashing the island. About eleven and one half inches of rain fell at Grand Cayman Island during the 24 hours ending at 7 a.m. (i.e. 0600 h) with 7.80 inches during the six hours between 1 and 7 a.m. (0000-0600 h, 30 October)". An extreme minimum pressure of 920 mb was calculated for Hurricane Hattie at 1600 h the same day (Dunn and others, 1962, 116). As the storm moved landwards during the afternoon and evening of 30 October, it became clear that the centre would cross the coast nearer to Belize than Chetumal, and would cause great destruction. Winds near the centre were estimated at 150 mph, gusting to 200 mph, accompanied by high tides, torrential rains, and gale force winds, extending at 2200 h for 230 miles in the NE semi-circle, and over all of the Gulf of Honduras to the south-west.

At 2200 h, 30 October, Hattie was located at 17.8°N, 86.6°W, 100 miles ENE of Belize. At 0100 h, 31 October, it was 75 miles ENE of Belize. At 0300 h, 31 October, Hattie was within 30 miles of Belize, at 17.4°N, 87.8°W. Figure 2 shows the track of the hurricane based on aircraft penetration and radar fixes up to this time. Advisory 15 from Miami stated:

> "The area from Belize to Chetumal will have hurricane force winds all morning and tides will be 10 to 15 feet above normal with salt water flooding the low areas for many miles inland. Torrential rains will also add to the flooding. Highest winds are estimated at 150 mph near the centre and gales extend from the coast to 200 miles east of the centre. The most extreme conditions, 150 mph winds and 15 foot tides with huge waves, will occur at Belize in the next few hours and all precautions for the protection of life and property should be continued."

Even before this Advisory was issued, Belize radio had ceased to function (at 0300 h, 31 October) and the northern barrier and atoll reefs were experiencing hurricane conditions.

Hurricane Hattie in British Honduras Waters

The track followed by Hattie across the coastal area of British Honduras can be plotted from a variety of sources. These include (a) a few radar positions, given in Figure 2; (b) local barometric records; (c) eyewitness accounts of wind, weather and sea conditions; (d) physiographic effects on reefs and cays; and (e) vegetation effects, chiefly direction of fall of coconut palms. Eyewitness accounts in the reef area are few in number for several reasons. The hurricane

passed during the night and early morning, and this, together with the unusually severe conditions, impeded observation. The total population of the cays is at any time small; many moved to the mainland before the hurricane struck; many who remained were drowned, and a high proportion of those who survived have since moved to the mainland and cannot be easily traced. Appeals for information from persons on the cays at the time of the storm, made over the British Honduras Broadcasting Service Radio, met with no response. The most important sources of information are the lighthouse keepers, and also the Master of the m.v. Tactician, then in Belize harbour. Information from these sources is collected here; data derived from study of physiographic and vegetation change are not considered here, and have not been directly used to reconstruct hurricane events.

Half Moon Cay, Lighthouse Reef

Half Moon Cay lies 60 miles due east of Belize, and with Sandbore Cay at the north end of the same reef, was the first to experience Hurricane Hattie. Mr. Austin Garbutt, lighthouse keeper, and Mr. George Young, resident on the cay since 1928, state that the first sign of the storm came during the afternoon of Sunday, 29 October. Heavy swells from the east refracted into the southeast bay and washed over the main seaward sand ridge, 9-10 feet high, from about 1530 h. This heavy swell continued until dawn on 30 October, and was followed by calmer seas. It is interesting to note that this wave action is comparable to that experienced at the height of Hurricane Abby (1960) and Hurricane Anna (1961), and Mr. Young, who had seen many hurricanes before, including those of 1931 and 1945, was of the opinion on the morning of 30 October that the storm had passed. At 1530 h, when the swell began to break, Hurricane Hattie was just beginning to turn to the west, and the centre was located some 400 miles east of Half Moon Cay.

During the morning of 30 October, the wind was northerly, force 2-3, freshening in the afternoon and shifting to westerly about 1500 h. Force 5 winds continued from about 1500 to 2300 h, when they began to draw to the southwest and freshen further. Heavy seas began to overtop the seaward sand ridge continuously from about 2200 h. The aneroid barometer was falling rapidly at this time. By 0100 h, 31 October, the wind was southerly, blowing with hurricane force, and the aneroid reached its lowest level of 27.85 in, where it remained steady for 2-3 hours. Between 0100 and 0200 h the wind reached its maximum force, blowing from the south and southwest, and knocking many coconut trees down. South and southwesterly winds continued to blow hard until 0400-0500 h, and waves continued to wash across the cay until about 0400 h. By 0900 h, 31 October, the storm was clearly over, and the winds had fallen to force 4 or 5.

Sandbore Cay, Lighthouse Reef

Mr. Roy Young, Lighthouse keeper, survived the storm in a concrete hurricane shelter on the cay, despite extreme devastation which demolished the lighthouse and all other buildings and cut the cay into three parts.

As at Half Moon Cay, heavy swells were experienced on 29 October, but the leading edge of the storm itself did not approach the cay until the afternoon of 30 October. At 1300 h, 30 October, winds from the northwest did not exceed force 3-4. Heavy wave activity in advance of the storm had begun by 1430 h, and refracted waves broke heavily on both north and south shores. The concrete walk, 75 yards long, connecting cay and lighthouse, built in 1945, was very soon completely destroyed. At 1530 h Mr. Young was in wireless communication with Half Moon Cay for the last time. By 1600 h it was decided to move into the concrete hurricane shelter, as the wind was still rising. By this time the cay surface was covered with 1½ feet of water; an hour later this had increased to 2-2½ feet, and kerosene drums were beginning to float away. The wind was still northwesterly. By 1930 h, the wind was "very high", and the barometer was falling rapidly. At 2230 h, the sea had risen so much that the floor of the hurricane shelter, approximately 8 feet above the sea, was flooded to a depth of one foot. At midnight the wind dropped suddenly and the aneroid barometer reached its minimum of 27.4 inches. It remained at this level until 0130 h, 31 October, when it began to rise. Hurricane force winds returned from the south at 0100 h, and at the same time the water level began to fall. Mr. Young considered that the southerly winds following the calm were "much harder" than the northwesterlies preceding it. From about 0200 h, however, the wind began to fall, and drew round to the east. By dawn, 0700 h, the wind had fallen to force 7, northeasterly, with much rain.

All houses on the cay disappeared except the single concrete hurricane shelter. The lighthouse was demolished and all fishing boats disappeared. During the hurricane the shelter held four adults and five children, who would otherwise have lost their lives; afterwards they were joined by nine others from Northern Cay, and all managed to survive until taken off by a passing ship six days later.

Mauger Cay, Turneffe

Mr. Thomas Young, formerly keeper of the Mauger Cay light, states that during the evening of 30 October, the wind was from the north, and gradually increasing. At midnight the inhabitants of the cay went to the top of the lighthouse and spent the rest of the night there. By this time the wind was already blowing very hard, and continued to increase, still from the north, until 0400 h, 31 October, when it veered round to the southeast. From 0400 to 0600 h the wind blew with its greatest force, and all the houses on the cay were destroyed at this time. After 0600 h, the wind began to moderate, and continued to do so throughout the morning. There is no precise information on the height of the sea. Mr. Young states that it began rising late on 30 October, and at dawn on 31 October covered the cay to a depth of 5-6 feet.

Cay Bokel, Turneffe

Only sparse information is available from Cay Bokel, where six people died. At 1700 h, 30 October, the wind was already strong, and accompanied by heavy rain. At 2100 h, the wind had intensified to hurricane force, from the northeast, and houses were collapsing. At midnight, 30-31

October, the wind abated suddenly, and there was a lull of 10 minutes, before the wind returned from the southeast. Heavy seas covered the island and washed people away. At 0500 h on 31 October the wind began to fall, and the sea surge to abate. (This information is given in writing in a report at the Chief Secretary's Office in Belize, but I have not been able to discover its source. The times given are clearly incompatible with information from other cays; the occurrence of a brief lull so far south is interesting. Discrepancies are clearly the result of the very severe damage caused by the storm; the island completely disappeared and even the lighthouse overturned.)

Cay Caulker, Barrier Reef Lagoon

Cay Caulker lies to the north of the hurricane track, some 20 miles northeast of Belize. The police constables on the cay made the following report. The wind began to freshen at 1600 h, 30 October, blowing from the northwest. At 1700 h heavy waves were breaking on the beach, and the wind was increasing. At 2300 h, the wind changed from northwest to northeast, and was estimated to be gusting from 175-200 mph. At midnight, large swells were rolling over the cay near Cay Caulker Village. The schoolhouse collapsed under the stress of wave action at 0300 h, 31 October, with the loss of 14 lives. Most of the damage was said to be caused by five large distinct waves. The highest water mark was 15 feet above sea level, and the sea did not recede until 0900 h.

Belize City

Advisory 11 from the Miami Weather Bureau, the first to warn of hurricane conditions on the Yucatan coast, was received in Belize at 0700 h, 30 October. As a result, at 0800 h, Government ordered the hoisting of the warning signal "Red I" throughout British Honduras, and of "Red II" in Corozal District, where the storm was expected to strike. At 1100 h, "Red II" was ordered throughout the country.

A number of instrumental records are available from Belize City (figure 4). The most reliable is probably that from the Meteorological Service, Stanley Field, 14 miles west of Belize, equipped with a barograph and Dines anemometer; copies of these records have been published by Dunn and others (1962, 116-117). The official Belize barograph was inadequate to record the lowest pressures experienced during Hurricane Hattie; the partial trace in Figure 4 has been supplied by Colonel Fairweather, B.H.V.G. I am also grateful to Colonel H.P. Charnock Wilson for the use of his private barograph trace, Figure 4, the only complete record for Belize City itself. Finally, the Police Log Book of Hurricane Hattie contains regular readings of the Police Station mercury barometer, and readings from Mr. [illegible].S. Porcher's aneroid, also at the Police Station.

Pressure in Belize fell slowly but steadily from 1200 h (29.8 in) to 2200 h (29.6 in) on 30 October, and then began to fall more rapidly. At midnight, 30-31 October, with pressure at the Police Station 29.53 in, the wind increased to gale force, from the north-north-west, and rain began to fall. Wind speeds at Stanley Field at this time varied from

15-30 mph, force 5-6. At 0100 h, 31 October, the Police barometer fell to 29.4 in. According to the Police Log Book winds had already reached hurricane force, but the Stanley Field anemometer at this time recorded no gusts in excess of force 8, 47 mph. Electric power failed in Belize at about this time, but radio transmission continued using emergency generators. At 0200 h, the Police Log recorded winds of "probably" 100 mph. (cf. Stanley Field winds ranging from 20-60 mph), still from the NNW; pressure had fallen to 29.2 in. At 0300 h, the emergency generators failed and BHBS ceased transmission. By 0400 h, the Police barometer read 28.68 in, and the wind was reported as rising steadily, and gusting probably to 150-200 mph. Buildings in Belize were beginning to disintegrate, and roofs were being torn off. Stanley Field at this time recorded winds of 30-80 mph. At 0500 h, the lowest reading was made on the Police barometer, 28.35 in. The Charnock Wilson barograph read 28.5 in. at 0500 h, and 28.45 in at 0600 h. High winds and heavy rain continued. At Stanley Field the wind continued to increase, gusting to 115 mph when the record ceased shortly after 0500 h (Figure 5). Between 0400 and 0500 h, the wind direction changed from NNW to N, and then slowly began to draw to the east. Easterly winds were continuous from about 0700 h.

At 0600 h, pressure began to rise rapidly, shown in Belize by the Police and Charnock Wilson barographs, and by the Stanley Field barograph. Minimum pressure as the hurricane centre passed to the southeast of Belize was probably about 28.4 in. in the City and 28.7 in at the airfield 14 miles to the west. According to Dunn and others (1962, 116) the pressure gradient between the airfield and the hurricane eye 20 miles southeast of Belize was some 45-50 mb, 1.5 in. At 0600 h also, the wind reached its greatest intensity. No instrumental records are available, but according to Dunn and others (1962, 117) "reliable estimates" put the wind speed at 140-160 mph, perhaps gusting in excess of 200 mph. Between 0700 and 0800 h the wind fell considerably to about 70 mph, and after 0900 h declined further to 30-60 mph (Stanley Field). As the wind drew to the east and reached its maximum force at about 0600 h, the sea-level began to rise. At 0600 h there was 1 foot of water in the Police Station yard; by 0800 h the depth had increased to 10-12 feet. The whole city was inundated, the streets filled with thick mud, and mud, sand and weed thrown high above the extreme high surge level by the considerable wave action which still continued. By 1030 h the wind had fallen in Belize to "light to moderate", the barometer at the Police Station had risen to 29.5 in, and the water in the streets had receded to a depth of only 3 feet. At mid-day, however, there was still 2-3 feet of water in many streets, and people were paddling about in doreys (dugout canoes). First radio contact with the outside world was made at 1500 h on the day of the hurricane, and first assistance arrived with a scheduled flight of TACA airlines on the early morning of 1 November.

Barrier Reef Lagoon

The most complete record of changing conditions during Hurricane Hattie comes from m.v. Tactician, a new Harrison Line vessel on its first voyage to Belize. The following account is based on observations made by the Master, Captain W.S. Eustace, and very kindly placed at my disposal.

On 29 October, the Tactician was at Stann Creek. The barometer was steady at 29.8 in; and the wind was northwesterly, force 3. In the evening the ship returned to Belize. On the following day, 30 October, at 1000 h, heavy seas were reported breaking on the outer reefs, and it was decided to move from Belize harbour to a point south of Grennel's Cay (Triangles). The ship anchored in 9-11 fathoms water, 5 miles south of Grennel's Cay, at 1600 h. The barometer was still steady at 29.7 in; the wind had increased to force 5. The sky was overcast, with alto-nimbus, and there were light showers. At 2000 h the barometer read 29.65 in, temperature 75°F, sky heavily overcast, with moderate showers. At midnight, 30-31 October, the wind was west-north-west, and squally; barometer 29.45 in. The showers continued.

In the early hours of 31 October the wind increased, reaching force 10 by 0200 h, but still WNW. The sky was overcast, with frequent showers, and a short sea was rising. Captain Eustace could still see the lights of Belize, English Cay and Colson Point at this time. At 0215 h, the winds reached hurricane force and the ship began to drag her anchors. Observation of the lights showed drift of 2 miles in 25 minutes, beam on to the wind and rising sea. Captain Eustace notes that "Being in the lee of the land it is rather surprising that the latter was so high and rough, as if the wind was blowing down, rather than horizontally." He was unable to bring the ship up into the wind, and continued to go astern on the engines. By 0300 h, Captain Eustace found that "the wind was stronger than any I have ever experienced in my life." It continued from the WNW; the air was full of sea, spray and rain; and the barometer, at 28.5 in, was falling rapidly. The Tactician had developed a list of 20° with the wind, and the steep short sea pushed her another 15-20°. At 0400 h, the wind was estimated at 150 knots (175 mph), WNW. The barometer continued to fall steadily, and had reached 27.67 in. Rainfall was now heavy. At 0500 h the barometer read 27.30 in, and at 0515 h 27.40 in. The wind dropped suddenly at this time to a moderate breeze.

During the lull, which lasted three-quarters of an hour, a "very sickly" moon and a few stars could be seen, partly obscured by scud from the ESE. A confused sea and swell came predominantly from the SE, gradually increasing until at 0600 h the wind settled in again from the SE, force 5-6. The barometer, now reading 27.6 in, continued to rise. By 0615 h, with the barometer 27.72 in, the wind was back at hurricane force, and the sea rose likewise. This time it seemed to have more force than before the lull, partly, Capt. Eustace surmised, because of deeper water over the reefs as a result of the storm surge. Wind, spray and heavy rain penetrated everywhere. The ship again swung beam on and heeled over; and again she was forced to go astern on the engines, dragging the anchors. At 0700 h the barometer stood at 28.10 in. and the wind, from the ESE, was gusting to over 170 mph. Rain came in squalls, but the heavy cloud cover was noticeably higher. By 0900 h the wind had eased to force 12, and the ship began to respond at last to the engines. The barometer had risen to 29.33 in; visibility was 3 miles. At mid-day, with wind force 9, the steep rise of the barometer was checked at 29.63 in. A cay could be seen at a distance of 4½ miles, probably one of the Colson Cays. Cloud was forming and lifting. At 1300 h the Tactician returned to Belize with an easterly gale blowing. "The sea was a milky colour", noted Capt. Eustace, "littered with palm trees and many dead fish. On reaching the Belize anchorage depths about 4 feet more than usual were noted" (as a result of the storm surge).

The Tactician was clearly in the direct path of the hurricane as it crossed the barrier reef lagoon. The lowest pressures recorded were 931.5 mb (27.51 in), corrected to 27.40 in, on the mercurial barometer, and 27.30 in. on the aneroid, both at 0500 h. The instruments were checked a few days later at Houston, USA, and found to be correct.

Tobacco and South Water Cays, Barrier Reef

Brief accounts are available from inhabitants of these islands, which are only 5½ miles apart. Both lie well to the south of the hurricane track. At Tobacco Cay, high winds are said to have begun during the evening of 30 October, mainly southwesterly. In the early hours of 31 October the wind moved to the south and increased in violence; coconut trees began to fall at about 0800 h. The sea level did not rise, but high waves washed over the margins of the cay, especially on the south side. At South Water Cay Mr. Joe Garbutt states that high winds began about 1900 h, 30 October, from the northwest. About 0100 h, 31 October, the winds moved to the southwest and continued in this quarter till 0500 h. From then until 1100 h southerly winds blew with great violence; by mid-day the wind was abating. The cay was not inundated, but high waves washed over the south and southwest shores.

Stann Creek and Nearby Area

The District Commissioner, Stann Creek, which suffered very heavy damage, reports as follows. At midnight on 30-31 October, heavy rain was falling, and the wind was increasing. By 0200 h, 31 October, winds had reached gale force, blowing from the west. Between 0330 and 0430 h the wind gradually shifted from west to south, continuing to blow at hurricane force, and gradually moving to the southeast. Estimated windspeeds reached 150 mph, with gusts to 200 mph. At 0500 h the sea surge began, reaching its maximum height at 0900 h. Low-lying areas in Stann Creek Town carried 10-12 feet of water, and near the Police Station and in Front Street the water was 4-5 feet deep. Between 0900 and 1000 h the wind began to abate, the gusts became weaker and more sporadic, and the water began to recede. By 1100 h it was possible to walk through the streets.

The storm centre appears to have passed directly over Mullins River, 10 miles north of Stann Creek, where all but three houses out of 300 were destroyed. Here the storm surge is said to have risen as high as 20 feet above sea level.

Melinda Forest Station is situated 5 miles inland from Stann Creek Town, in the Stann Creek Valley; Mr. R. Langley gives the following account of conditions. The wind was blowing to a storm by midnight on 30-31 October. By 0200 h, 31 October, the wind was "strong" and westerly. Hurricane force winds blew from the west until 0715, when the wind dropped suddenly and there was a distinct lull until 0800 h. Immediately after the lull the wind returned with full hurricane force, but blowing from the east, and a little from the southeast. By 1100 h it had abated somewhat, and by mid-day approximated only to a "very heavy storm". It is significant to note that the three-quarter hour lull was not experienced at Stann Creek, only 5 miles away.

Mango Creek

Mr. I.A. Fadden, Belize Estate and Produce Company Manager at Mango Creek, a coastal inlet near Placencia, 28 miles south of Stann Creek, made barometer readings during the storm (Figure 4). At midnight, 30-31 October, pressure stood at 29.75 in; it fell steadily throughout the early hours of 31 October, reaching a minimum of 29.01 in at 0930 h. The first heavy gusts of wind came at 0430-0500 h from the south-south-west, and then increased to an estimated 100 mph by 0730 h. At 0930 h the wind shifted suddenly to the south, and the highest winds of the whole hurricane were experienced at about 1000 h. At 1110 h, the wind had shifted to south-south-east. After 0930 h the barometer rose very rapidly, and by 1300 h was almost back to the pre-storm level.

Punta Gorda

Punta Gorda is situated on the coast of the Gulf of Honduras, near the southern borders of British Honduras. The Acting District Commissioner made this report: "At about 3.00 a.m. (0300 h, 31 October) a strong wind of approximately 35 mph began blowing in Punta Gorda. The velocity of the wind increased to such an extent that at day-break, about 6.0 a.m., the people were informed to vacate their homes to make use of the approved shelters. By 7.00 a.m. the velocity of the wind had increased to 45-50 mph and became stronger still in the course of the day, reaching approximately 75-80 mph between 12 and 2.00 p.m. when it began to subside gradually. By 7.00 p.m. the wind had finally calmed down."

Other Areas

Two inland records may be added to complete the picture of Hurricane Hattie's passage across the country. At Cayo, 60 miles WSW from Belize, winds "a little above hurricane force" blew from 1200 to 1500 h on 31 October. "Shortly afterwards" the Moran and Macal Rivers rose in places by over 40 feet, a response to torrential rains in the hilly country to the south. In El Cayo town itself the river rose to within 2-3 feet of the roadway on the Hawkesworth Bridge, 52 feet above the streambed. Similar floods occurred at several places along the northern edge of the Maya Mountains: at Barton Creek the road was submerged 8 feet deep and at Roaring Creek it carried 12 ft. water. This flooding lasted one day: in some villages a second flood occurred a day or two later. Near the sea, with impeded drainage, excess runnoff remained on the land for a considerable time. There are no estimates of the amount of rainfall during the storm, but the 11.5 in. in 24 hours at Grand Cayman Island gives some indication of magnitude. Winds were sufficient to fell trees along the whole of the Belize-Cayo road, at least as far as Benque Viejo, though the greatest numbers of fallen trees are seen between Belize and Roaring Creek and points south. Tree-fall was moderate in the Mountain Pine Ridge area. Direction of fall was generally east to north. Catastrophic forest destruction occurred in the Maya Mountains, especially in the Cockscomb Basin, and points southwest to Quartz Ridge, but any detailed report on these is outside the scope of this paper.

At Orange Walk, 42 miles NW of Belize, winds of 40-45 mph were experienced between midnight and 0830 h on 31 October. Gusts were estimated at 65-70 mph.

Changing Wind and Wave Conditions, 2100 h 30 October - 1200 h 31 October

The foregoing narrative of hurricane conditions at locations throughout the British Honduras reef area and inland gives a general, though patchy, picture of changing wind and sea conditions as Hurricane Hattie passed. This information is summarised in approximate fashion in a series of charts at hourly intervals from 0900 h on 30 October to 1200 h on 31 October (Figures 6-10). These diagrams are derived only from actual weather conditions, by plotting wind direction at hourly intervals for each reporting station, together with other relevant information, such as barometric records and radar fixes of the storm centre. Wind streamlines were then drawn to fit these observations and the approximate centre of the storm at each time. Each hourly chart was computed without reference to those immediately before and after; hence, if the charts are combined, the resulting hurricane track (Figure 11) looks somewhat erratic, though this may well have been the case. The outer edge of the streamlines delimits in a very approximate way the limit of hurricane force winds. Using these charts, the general sequence of wind directions at any one place, other than those for which we have eye-witness accounts, can be determined. For points north of the storm centre, the winds were generally, northwest, north, northeast, and east; and for points south, generally southwest, south, southeast and east.

Storm Surge

There is no precise information either on wave conditions during the hurricane or on the limits of the storm surge which accompanied it. The storm surge would seem to have been less severe on the outlying reefs and atolls than on the mainland coast, where a shallow offshore shelf presented optimum conditions for high surge development. Thus at Sandbore Cay, Lighthouse Reef, near the storm centre, the surge reached its greatest height of about 9 feet above normal sea level at 2230 h 30 October, $1\frac{1}{2}$ hours before the passage of the centre itself. No appreciable surge was recorded at Half Moon Cay, 20 miles to the south. Information for Turneffe is very sparse indeed: the surge at Mauger Cay reached its maximum during the early hours 31 October, with heights of perhaps 5-6 feet. There is no further information on points to the south, but most of the small eastern cays show signs of complete inundation. It is difficult on these more exposed cays to separate the effects of intense wave action from those of a true storm surge. On the barrier reef and mainland coast we have rather more data, though the accuracy of some reports is questionable. The most trustworthy record is that of Belize, where the surge began immediately <u>after</u> the passage of the storm centre 15-20 miles to the southeast. Between 0600 and 0800 h on 31 October water level rose to a maximum of 12 feet above normal (the astronomical tides on this coast rarely exceed one foot, and may be disregarded here); the fall in level from the

peak of the surge was much slower than the rise, and at mid-day sea level was still 3-4 feet above normal. This is shown not only by the Belize records, but also by that of the Tactician at 1300 h in Belize harbour. There is no information on the extent of the surge along the uninhabited mainland coast north of Belize, and information from the barrier reef cays is sparse. Cay Caulker reports a high water mark of 15 feet, the water not receding until 0900 h; this probably refers to the highest water mark of wave action, and the true surge height was probably very much lower. On morphologic grounds it was probably less than 6 feet, and may only have been 2-3 feet. Cay Caulker lies 30 miles north of the storm track. At Ambergris Cay, 40 miles north, the surge probably did not exceed 2-3 feet.

South of the storm track, information is again limited. Stann Creek, 9 miles south of the storm centre, has well-attested reports of a surge beginning at 0500 h and lasting till about 1000 h, reaching 10-12 feet above normal. The times and extent of the surge are similar to those at Belize. However, no surge occurred at Tobacco or South Water Cay, 20 miles south of the storm track, on the edge of the coastal shelf. At Mullins River, where the storm centre crossed the coast, there is a rather dubious report of a maximum surge level of 20 feet; again, this probably refers to the maximum height of wave action. There is no information on surge levels on the mainland coast south of Stann Creek.

Figure 12 summarises this very sketchy data. The figures for Sandbore and Mauger Cays on the atolls are not really comparable to those on the mainland, since open-ocean levels must have been considerably lower than coastal figures on account of the shelf effect. Much information has accumulated on hurricane-induced surges (Hadfield and Miller, 1957; Hubert and Clark, 1955), and empirical relationships have been found between height of storm surge, lowest central pressure, and distance north and south of the hurricane track (Hoover, 1957; Conner, Kraft and Harris, 1957; Harris, 1956, 1957, 1959). Using Conner, Kraft and Harris's formulae, with a lowest central pressure of 27.3 in, the maximum surge should have reached approximately 13 feet. Hoover's results give rather higher figures, of over 16 feet on the basis of Gulf Coast hurricanes, and over 15 feet on the basis of Atlantic coast storms. The order of magnitude is clear. Hoover (1957, 174) also shows that the highest surge generally occurs 10-15 miles to the right of the storm centre (facing the direction of movement) in Gulf Coast hurricanes, and 20-30 miles to the right in the case of those on the Atlantic coast. In any one storm the point of maximum surge, and the level of the peak surge, will clearly depend on bottom topography, shoreline orientation, angle of approach and other factors, in addition to the magnitude of the storm. It is reasonable to suppose that Hurricane Hattie's surge resembled previous surges. However, the angle of approach would tend to give unusually high levels in the lagoon segment between Stann Creek and Belize, so that the high report from Mullins River cannot altogether be excluded. Disregarding this channelling of the approaching surge, the Belize record of 12 feet 20 miles north of the storm centre may have approached close to the maximum surge level; up to 15 feet may have occurred in the Sibun River area. South of Mullins River one would have expected a rapid falling off in maximum level. The channelling effect of angle of approach on the shallow coastal shelf may have increased the ordinary surge by up

to 4-5 feet at Stann Creek. The very rough curve in Figure 12 b gives an indication of the surge-spread on the mainland coast. It must be stressed that as a result of the advance of the surge over the 10-20 mile wide coastal shelf, the mainland coast surge was undoubtedly both higher and of greater lateral extent than on the barrier reef or on the atolls. It might be noted that the hurricane surge during Hattie was higher than most recent Gulf of Mexico hurricane surges (Dunn and Miller, 1960, 219), and was similar to the open coastline levels during Hurricane Carla of 1961 (Dunn and others, 1962, 113).

There are few records of the "forerunner" or gradual rise of sea-level over a period of up to several days preceding the storm, though a slight rise in sea level accompanied the heavy swells which struck the outer atolls during the two preceding days. The first distinct sea-level rise was generally noted only a few hours before the hurricane, i.e. during 30 October.

Wave Action

Superimposed on the general rise in sea-level, and even more difficult to consider, is the effect of wave action. Observational data on waves during Hurricane Hattie are completely lacking, except for the Cay Caulker report that most of the damage was caused by five distinct waves. Since hurricane waves are wind-generated, it is reasonable to suppose that highest waves will be produced in the northern (right-hand) sector of the storm, where winds are moving in the same direction as the storm itself (Pore, 1957). Wind speed may be estimated at 150 mph; these high winds acted in an E-W direction, toward the British Honduras coast, from the time when the storm began to turn westwards on 29-30 October, 350 nautical miles east of Belize. Empirical tables relating wave characteristics, fetch and wind speed (e.g. Bretschneider, 1952) indicate that with wind speeds and a fetch of this magnitude, waves will be over 60 feet in height, with periods of more than 16 seconds. Normal wave period observed on the outer reefs varies from 5 to 7 seconds. Alternatively, Cline's (1926) rough empirical method (wind speed divided by 2.05 gives wave height) gives even greater heights; Japanese experience in the Pacific would suggest heights of more than 40 feet (Dunn and Miller, 1960, 101). These are all open-ocean figures, and waves of this magnitude have occasionally been observed during hurricanes. However, it is questionable whether such waves were experienced in the British Honduras reef area. If such waves were generated, and formed recognisable wave trains, they were probably confined to the open sea north and east of Lighthouse Reef; they may have helped in the destruction of the Sandbore Cay Lighthouse. Between the atolls and in the barrier reef lagoon, however, local bottom relief, shallow water, and varying wind direction may all have limited wave development. South of the storm centre, while many accounts speak of even more violent winds immediately after the central calm, waves were unlikely to have been so great, because of restricted fetch as the winds blew counter to the direction of hurricane movement. Even so, considerable damage was caused near deep-water areas, as at Cay Bokel.

As will be apparent in succeeding chapters, damage due to waves, while considerable, hardly seems to indicate the truly monstrous waves suggested by wind speeds. Recognisable wave trains were probably not well developed near the storm centre itself. Windspeeds were so high that the air-water interface became indistinct: several accounts speak of the air being full of spray, and of salt water 'raining' in through open roofs. The sea surface was probably highly confused, with short, very steep, but only moderately high waves (perhaps 20 feet) from many directions, depending on local winds. This may have lessened the erosive potential of the waves (Arakawa, 1954).

Direction of Water Movement

Figure 13 attempts to show, in a general way, the dominant directions of water movement associated with the hurricane, and the approximate area affected by the storm surge. Seas ahead of the hurricane were easterly; it was these swells, running ahead of the storm, which caused the early damage at Lighthouse Reef. To the north of the storm track, as the storm passed, sea movement continued easterly and northerly. Channel-cutting and delta-deposition at St. George's Cay, together with reports from Belize, Stann Creek, and the Tactician, of W to NW winds immediately ahead of the storm, indicate major water movements from the northwest in the northern barrier reef lagoon in the few hours immediately preceding the passage of the storm centre. Northwesterly seas may have played some part in the Crickozeen Creek slumping (Chapter 6). South of the hurricane track, the first swells were again easterly, but the main seas associated with the passage of the hurricane were southeast, south and southwest. This is shown by sediment deposition on cays, direction of tree-fall in inundated areas, and such miscellaneous indicators as the direction of fall of the Cay Bokel Lighthouse. This map of water movement may be compared with that showing direction of tree fall due to wind during the hurricane (Figure 63); the two show a considerable correspondence.

Rainfall

No rainfall information is available from British Honduras during the storm, since instruments were destroyed. It is in any case questionable whether standard rain gauges could give even an approximation of a mainly horizontal rainfall. The 11.5 inches in one day at Grand Cayman Island may be recalled; many instances in other hurricanes of over 20 inches in 24 hours have been recorded, mainly in mountainous areas (Schoner and Molansky, 1956). Rainfall is generally concentrated near and a little ahead of the storm centre (Miller, 1958). Rainfall in the Maya Mountains may have been more than 20 inches, judging from the extensive high floods. This excess run-off probably reduced salinity temporarily in the shallow northern barrier reef lagoon (cf. Goodbody, 1961), but this would have little effect on the reefs of that area, which were by then already dead.

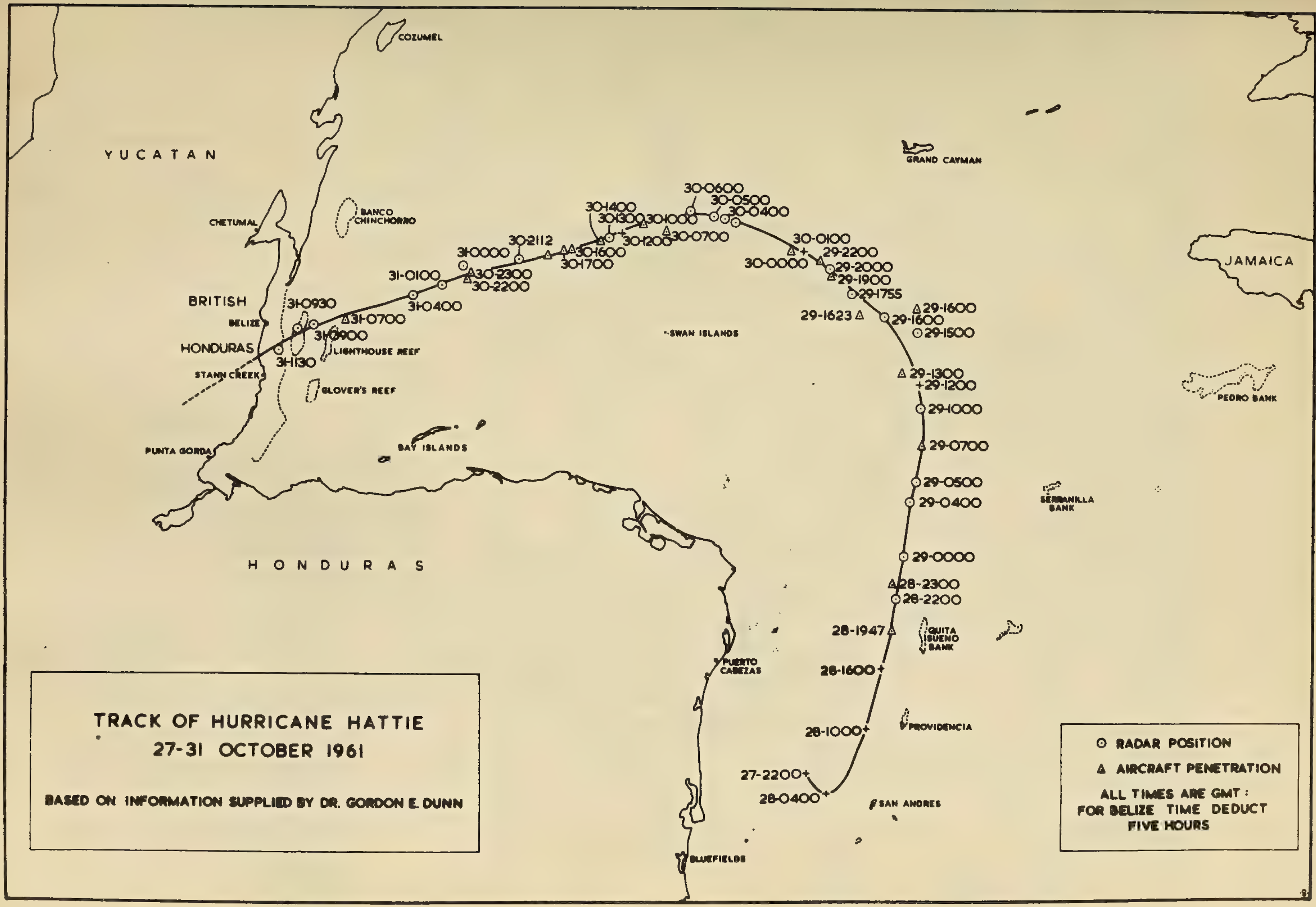

TRACK OF HURRICANE HATTIE
27-31 OCTOBER 1961
BASED ON INFORMATION SUPPLIED BY DR. GORDON E. DUNN
RADAR POSITION
AIRCRAFT PENETRATION
ALL TIMES ARE GMT: FOR BELIZE TIME DEDUCT FIVE HOURS
YUCATAN
BRITISH HONDURAS
HONDURAS
COZUMEL
CHETUMAL
BELIZE
STANN CREEK
PUNTA GORDA
BANCO CHINCHORRO
LIGHTHOUSE REEF
GLOVER'S REEF
BAY ISLANDS
SWAN ISLANDS
GRAND CAYMAN
JAMAICA
PEDRO BANK
SERRANILLA BANK
QUITA SUENO BANK
PROVIDENCIA
SAN ANDRES
PUERTO CABEZAS
BLUEFIELDS
27-2200
28-0400
28-1000
28-1600
28-1947
28-2200
28-2300
29-0000
29-0400
29-0500
29-0700
29-1000
29-1200
29-1300
29-1500
29-1600
29-1600
29-1623
29-1755
29-1900
29-2000
29-2200
30-0000
30-0100
30-0400
30-0500
30-0600
30-0700
30-1000
30-1200
30-1300
30-1400
30-1600
30-1700
30-2112
30-2200
30-2300
31-0000
31-0100
31-0400
31-0700
31-0900
31-0930
31-1130

FIG. 2

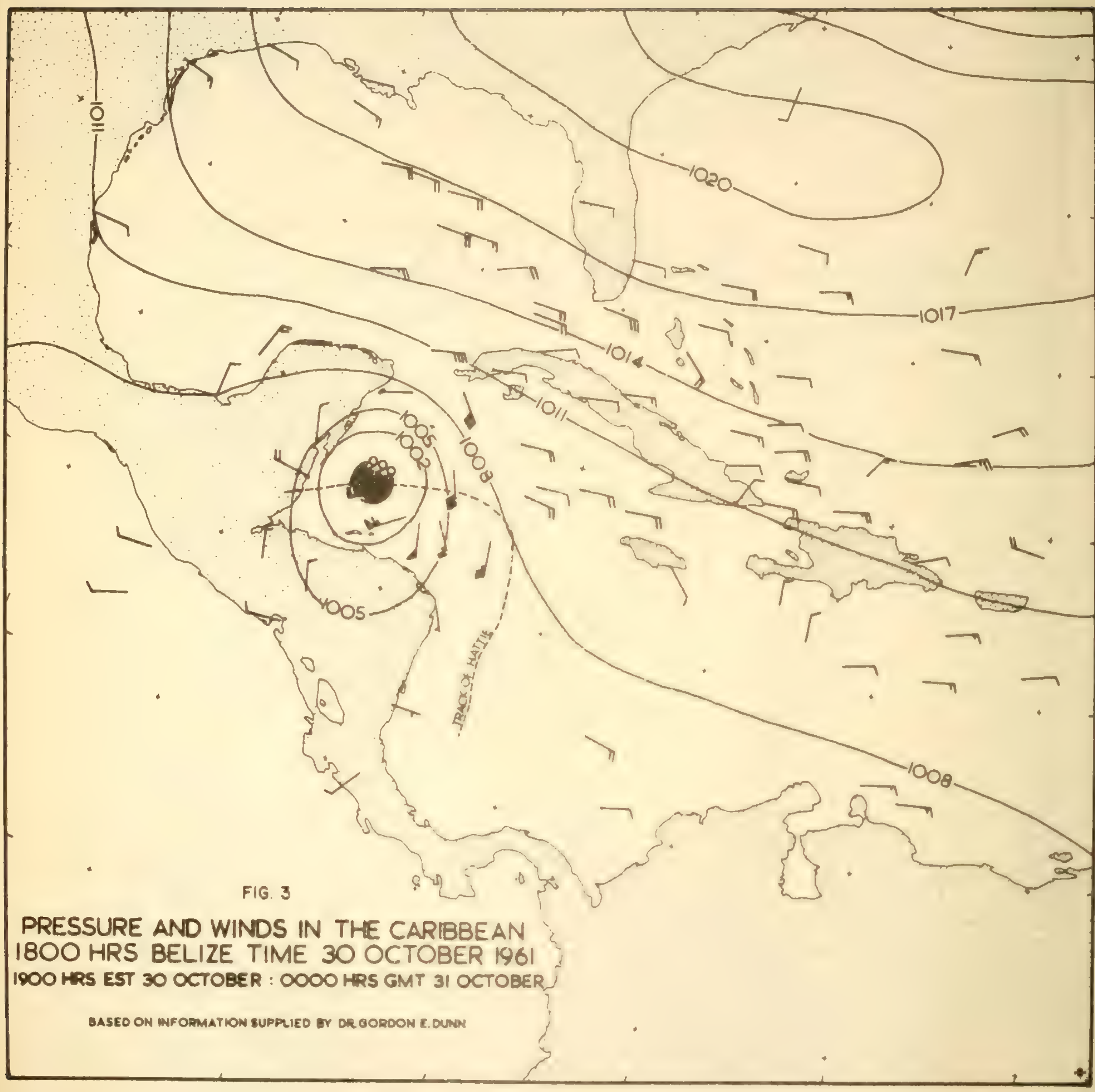


FIG. 3

PRESSURE AND WINDS IN THE CARIBBEAN
1800 HRS BELIZE TIME 30 OCTOBER 1961
1900 HRS EST 30 OCTOBER : 0000 HRS GMT 31 OCTOBER

BASED ON INFORMATION SUPPLIED BY DR. GORDON E. DUNN

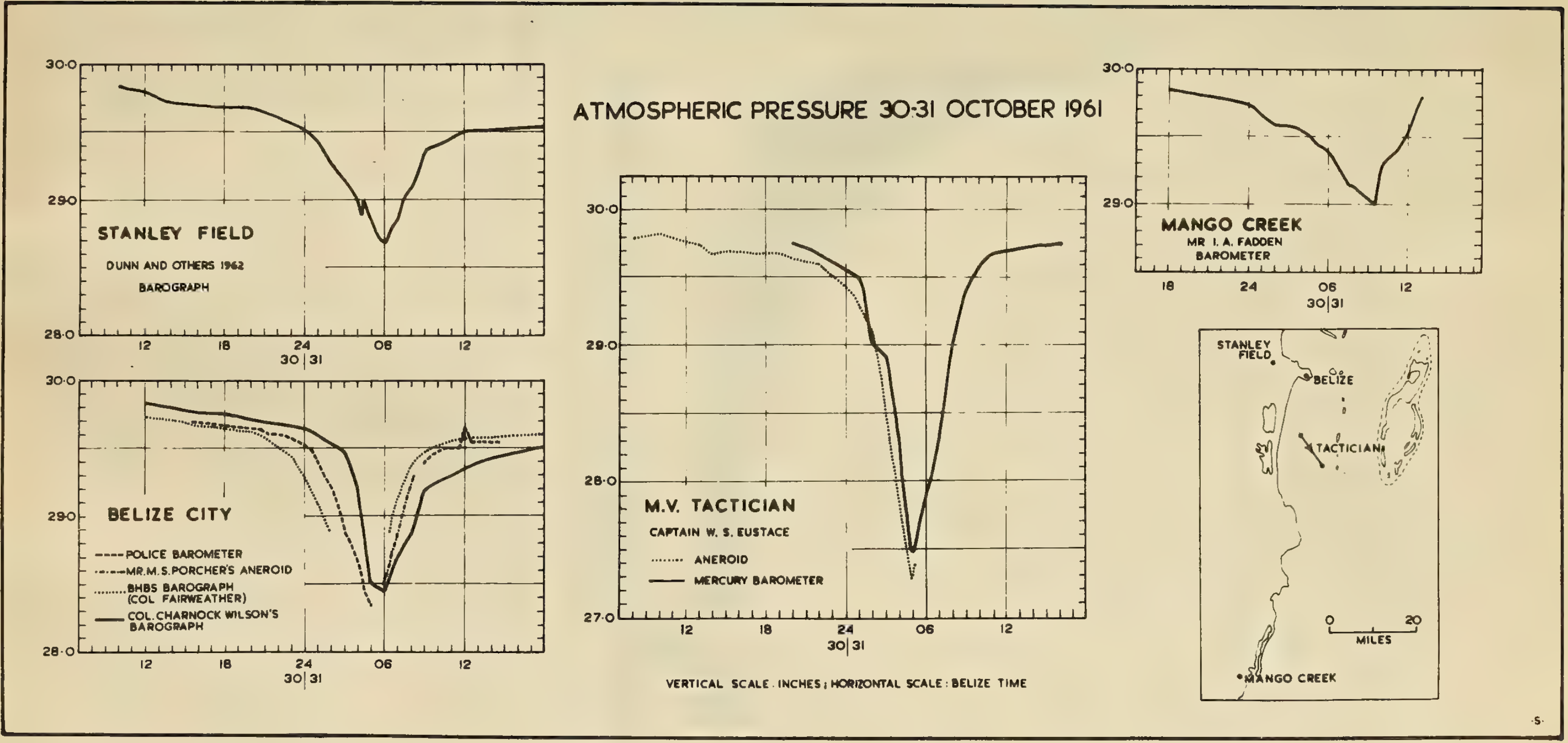

ATMOSPHERIC PRESSURE 30-31 OCTOBER 1961
STANLEY FIELD
DUNN AND OTHERS 1962
BAROGRAPH
30·0
29·0
28·0
12
18
24
06
12
30|31
BELIZE CITY
POLICE BAROMETER
MR. M. S. PORCHER'S ANEROID
BHBS BAROGRAPH (COL FAIRWEATHER)
COL. CHARNOCK WILSON'S BAROGRAPH
M.V. TACTICIAN
CAPTAIN W. S. EUSTACE
ANEROID
MERCURY BAROMETER
27·0
MANGO CREEK
MR I. A. FADDEN
BAROMETER
STANLEY FIELD
BELIZE
TACTICIAN
0
20
MILES
MANGO CREEK
VERTICAL SCALE: INCHES; HORIZONTAL SCALE: BELIZE TIME
·S·

FIG. 4

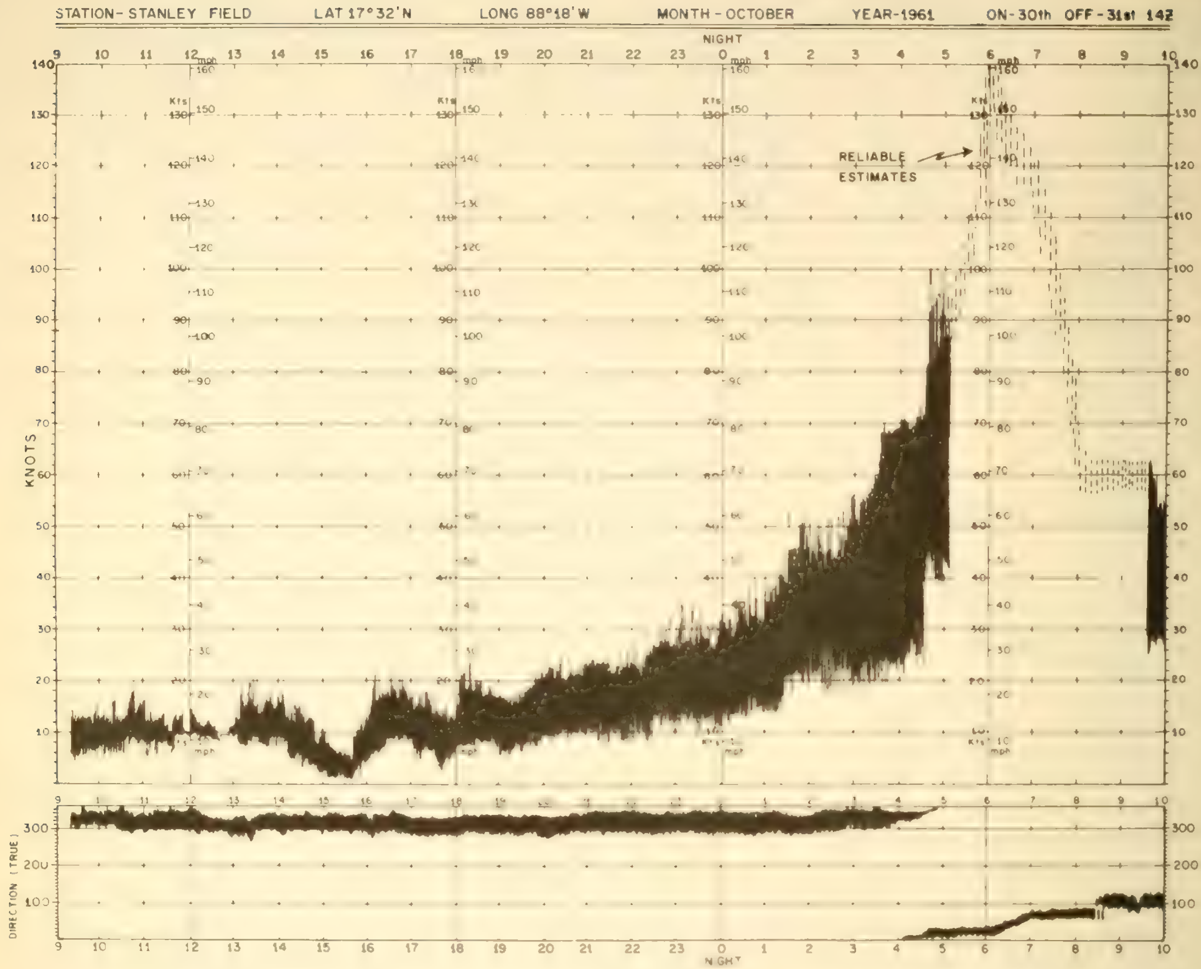
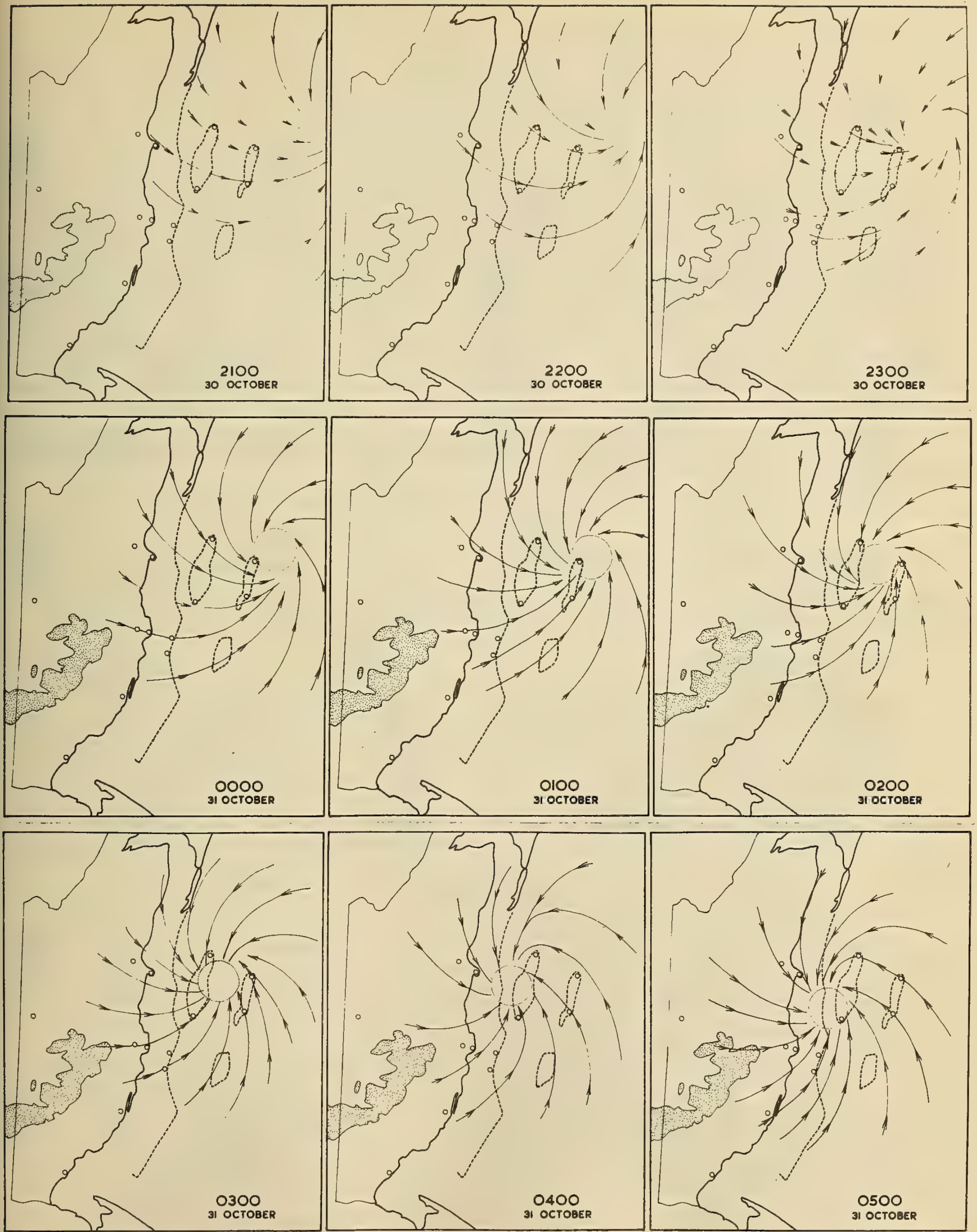
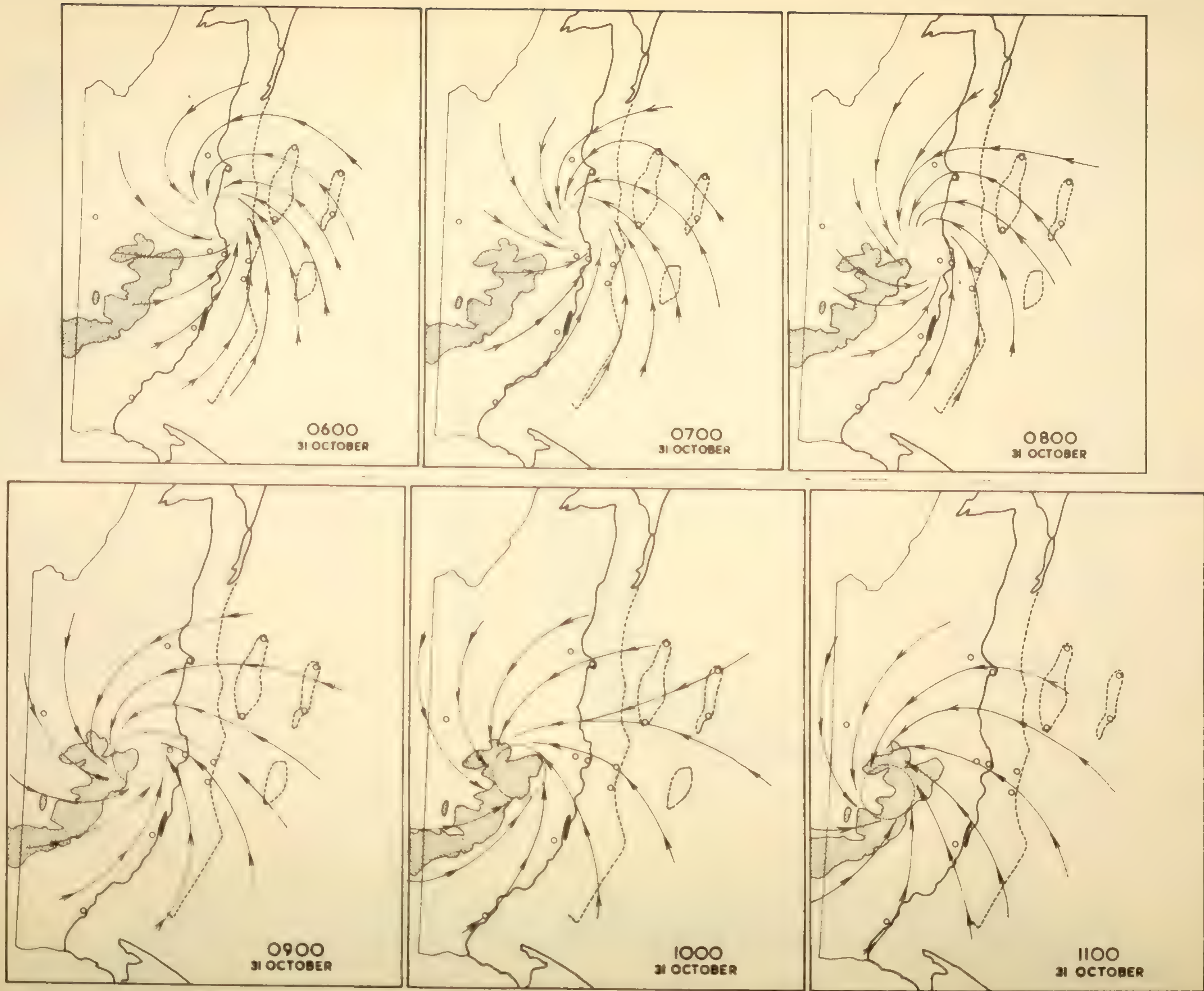


FIG. 5 - ANEMOMETER TRACE, STANLEY FIELD, BELIZE, 30-31 OCTOBER 1961. REPRODUCED FROM DUNN AND STAFF, 1962, COURTESY U. S. WEATHER BUREAU



FIGS. 6, 7, 8 - WIND STREAMLINES



FIGS. 9, 10 – WIND STREAMLINES

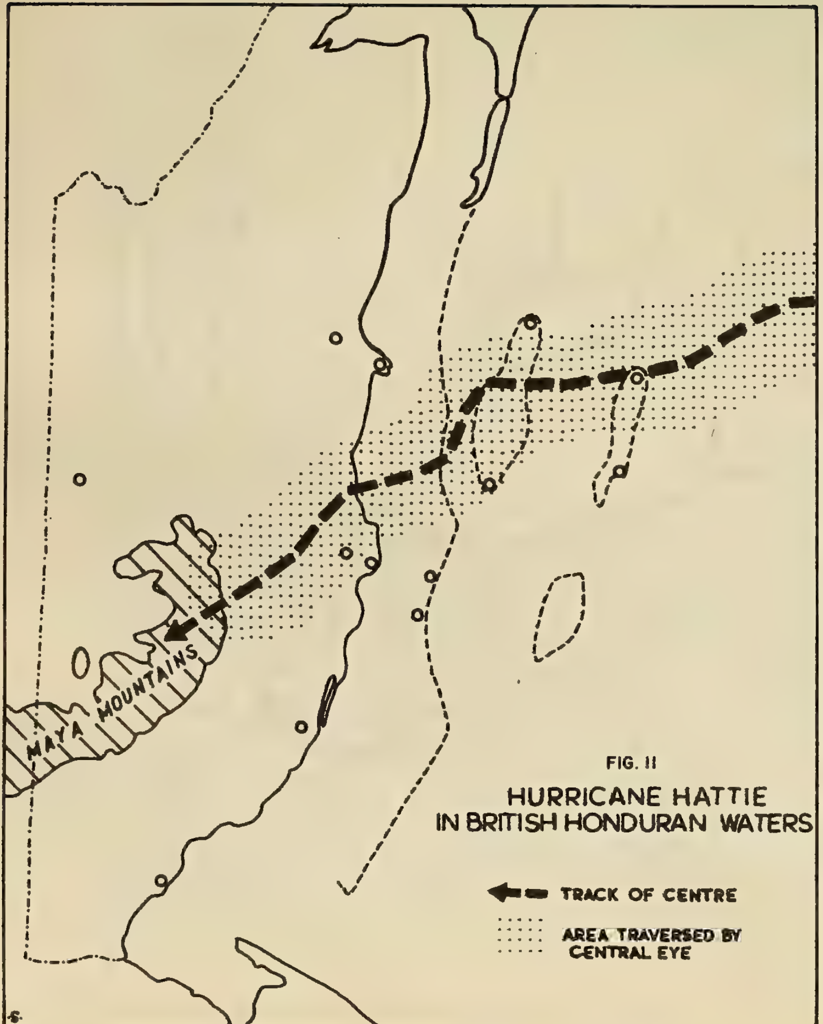
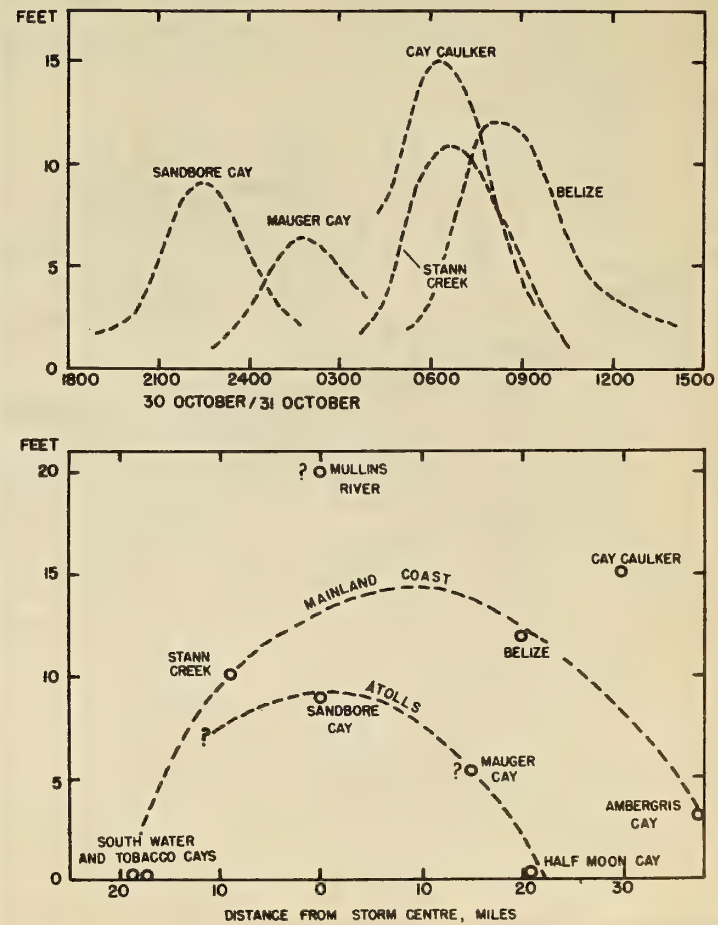


FIG. 11

HURRICANE HATTIE IN BRITISH HONDURAN WATERS

FIGURE 12, PROGRESS OF STORM SURGE



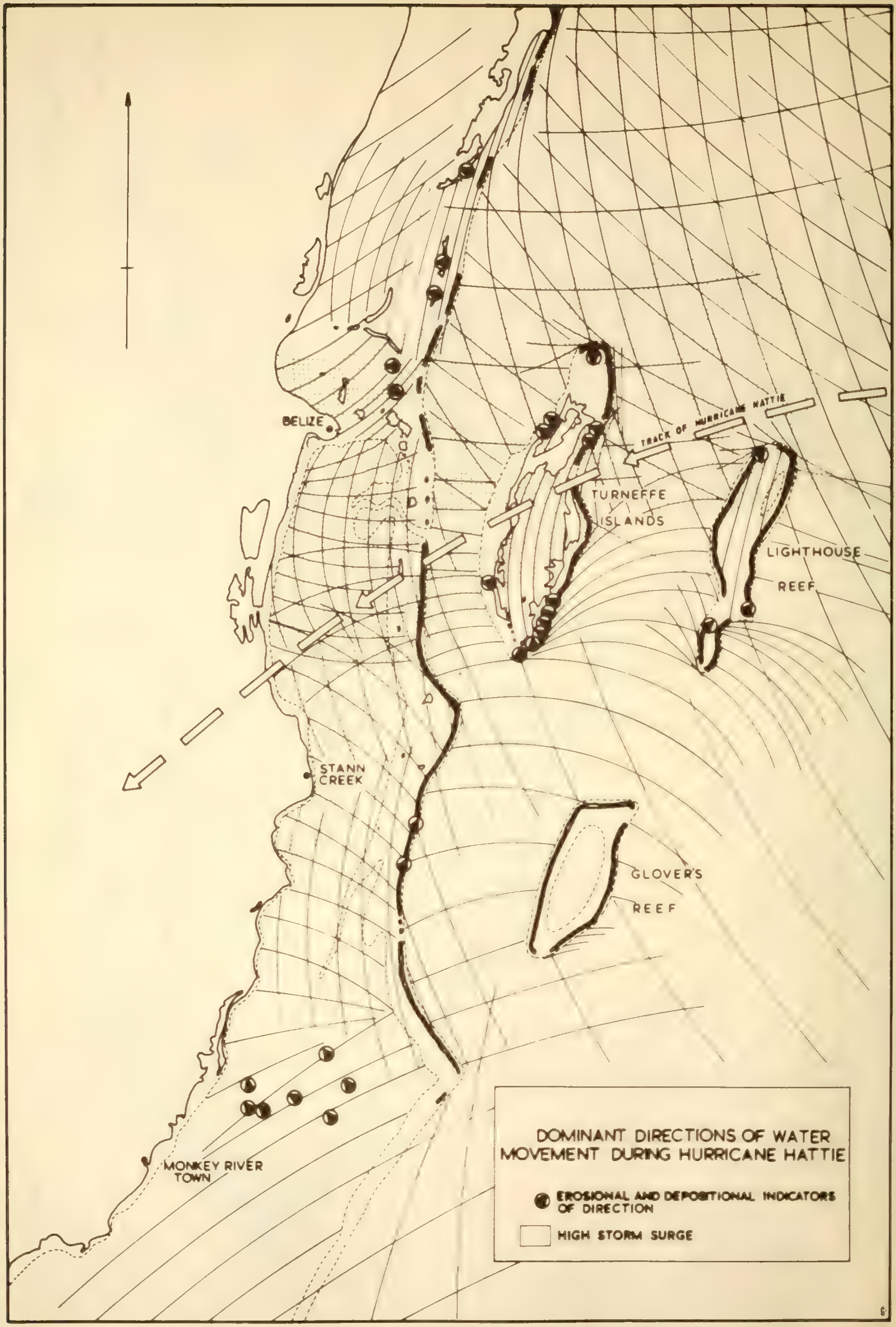

TRACK OF HURRICANE HATTIE
BELIZE
TURNEFFE ISLANDS
LIGHTHOUSE REEF
STANN CREEK
GLOVER'S REEF
MONKEY RIVER TOWN
DOMINANT DIRECTIONS OF WATER MOVEMENT DURING HURRICANE HATTIE
EROSIONAL AND DEPOSITIONAL INDICATORS OF DIRECTION
HIGH STORM SURGE

FIG. 13

III. REEF DAMAGE DURING HURRICANE HATTIE

Unfortunately only incidental observations could be made on living reefs during the 1962 expedition, and fresh seas prevented any underwater observation at all on the windward sides of both Turneffe and Lighthouse Reef. However, the whole length of reef round Turneffe, Lighthouse and Glover's Reefs, and along the barrier reef, was observed from the air and photographed at frequent intervals. These photographs could then be compared with a similar series made in 1961. Reefs were seen underwater at a number of places along the barrier reef itself. These observations are summarised in Figure 14. The main conclusion is the highly variable degree of reef damage, and the all-important role of the location and orientation of reefs in relation to hurricane winds and waves. Since the hurricane crossed the reefs almost at right angles, it is reasonable to assume that east facing reefs to the north of the storm track would suffer most severely from generally easterly and northeasterly winds and waves; and that reefs south of the storm track, facing away from the dominant winds or parallel to them, would suffer least damage. This did, in fact, occur, and hence there is no zonation of damage north and south of the storm track similar to that discernible on the cays.

Lighthouse Reef lay entirely to the south of the storm track, and its east reefs suffered remarkably little damage; groove-buttress systems seem unaltered for the length of the atoll. Minor damage is indicated at the north end of the east reef by shingle carpets on the reef crest; but greatest damage seems to have occurred on the east-west trending section of reef between Half Moon Cay and Long Cay. This is near the south end of the atoll, and aligned transverse to the southerly winds and waves dominant in this sector (Figure 13). The west reefs on this atoll were not well developed, and there is no means of assessing change. Lagoon reefs are unaltered, except in the northern lagoon, near Northern Two Cays, where some surface-breaking Acropora has been overturned.

Hurricane Hattie crossed Turneffe Islands near Pelican Cay. Northwards to Mauger Cay damage to the east reef has been heavy, especially on the reef crest and upper seaward slope. Fresh gravel carpets are spread across the reef crest, replacing living coral. Numerous corals have been thrown up at Cockroach Cays, including Diploria, Montastrea, Porites, Acropora, and Mussa angulosa (not previously recorded from this reef). Over the greater part of the seaward slope, however, the groove-buttress system is still preserved, and in some cases it is possible to identify particular reef-configurations on both pre- and post-hurricane photographs. South of Pelican Cay, degree of damage is very variable. Seas were mainly southerly, and either parallel to the reefs or nearly so. Damage is concentrated on reef segments oriented E-W or NE-SW, whereas immediately adjacent reefs, facing away from the southerly winds show little damage. A good example is found at Soldier Cay: north of the prominent Soldier Cay elbow the reef extends for several miles and seems little changed, but immediately south of this point damage increases and much debris is piled on the reef crest. Similarly, damage is considerable on the south facing reefs near Cay Bokel.

It is on the barrier reef itself, however, that reefs suffered damage to a heavy, even catastrophic degree. Hurricane Hattie crossed the barrier near Rendezvous Cay: on the barrier reef proper, and on numerous patch reefs immediately lagoonward of the barrier, between Rendezvous and English Cays, up to 80% of the reef corals have simply disappeared. Very heavy damage indeed has been caused as far north as Paunch Cay: but north of this point the reef is poorly developed and interrupted, and the degree of damage is uncertain. Between the Deepwater Channel and Rendezvous Cay the change is most dramatic: reefs which previously broke surface with distinctive assemblages of orange and yellow Acropora, now rise, greenish-white, ghost-like, and devoid of corals, from the surrounding blue water. No trace of any groove-buttress system can be seen along this reef, or indeed north of Cay Glory, 10 miles south of the hurricane track. Immediately north and south of the Cay Glory gap reef remnants on the seaward slope indicate the previous existence of a linear groove-buttress pattern, but this pattern does not become uninterruptedly apparent until south of South Water Cay. Changes on these barrier cays reefs can best be described by outlining underwater observations at a number of points.

Paunch Cay Reef

Dominant pre-hurricane species here were Montastrea annularis, Acropora palmata, A. cervicornis, and other assemblages similar to those of Rendezvous Cay, described below. From air photographs and underwater observation it seems probable that 90% of the living reef has been destroyed. The dominant surviving species is M. annularis, together with a few large overturned colonies, still living, of A. palmata, and patches of Porites astreoides, Dichocoenia stokesii, Siderastrea siderea, and especially Diploria labyrinthiformis, D. strigosa and D. clivosa. Millepora is particularly widespread at the present time. Only small specimens of Montastrea cavernosa were seen, and no A. cervicornis. Small corals such as Siderastrea radians and Manicina areolata are now absent. Cervicornis rubble is now accumulating on the reef flat as an embryonic cay (Chapter 4).

Sergeant's Cay Reef

The main species seen living here after the hurricane were M. annularis, Diploria, some Siderastrea siderea, and Porites astreoides. Round the seaward side there is a confused tangle of A. palmata with some still living. No A. cervicornis was seen, though the location of former patches is marked by well-defined rubble zones. There has been much destruction of Agaricia agaricites on the windward side, though a few patches remain alive. No "finger" Porites (P. porites, P. furcata, P. divaricata) was seen alive, but some dead and broken clumps were still recognisable. Other corals seen living in 1962 included Eusmilia, Isophyllia, and M. cavernosa.

Reef-patch south of English Cay

The reef patches between English and Rendezvous Cays attract attention because of their "bald" appearance. One was investigated about ½ mile south of English Cay. The coral fauna was previously comparable to that around English and Rendezvous Cay: a zone of A. palmata round the edges, especially on the windward side, A. cervicornis in the protected centre, and massive M. annularis on the outer slopes. Much dead A. cervicornis debris was seen, but none at all living. Conversely, A. palmata survived fairly well, though many large specimens were overturned, and some were dead. Most of the Agaricia was dead, together with nearly all the Porites porites. Scattered small colonies of Porites astreoides were fairly prominent in the general scene of confusion, together with much Millepora.

Rendezvous Reef

The centre of the hurricane passed almost directly over the Rendezvous Cay reef, a patch reef 450 yards long, elongated in a north-south direction, and 150-250 yards wide, rising steeply from water more than 50 feet deep. The edges of the patch, especially within 20 feet of the surface, were coated with coral before the hurricane, except on the west side, where a gap gave entrance to an anchorage near the cay carrying 4 feet of water. Otherwise the surface of the patch generally carried 1-2 feet of water. The pre-hurricane distribution of corals was investigated by diving and underwater mapping in 1959-60 by J.E. Thorpe; an outline map of the distribution of colonies has appeared (Thorpe, in Thorpe and Stoddart, 1962, Figure 4), together with a brief description (Thorpe and Bregazzi, 1960, 25-28). The main results are still in manuscript, and I am indebted to Mr. Thorpe for use of his unpublished charts. I also became familiar with this reef during residence in 1959-60, and a visit in 1961; many air and underwater photographs are available to supplement Thorpe's map. After the hurricane, a large number of air photographs were taken on two separate occasions, and two days were spent diving on the reef itself and taking underwater photographs. Figure 15 summarises the main changes in the distribution of reef corals: Part A is taken from Thorpe's published map; Part B is a compilation map from 25 air photographs, in colour, taken at heights of 100-300 feet in April and May, 1962. The second map is obviously much less reliable than the first, but there is no doubt that it reflects fairly accurately the magnitude of changes due to Hurricane Hattie.

Before the hurricane, the reefs could be described as falling into four divisions:

(a) the reefs on the west side, south of the anchorage gap; with a crest of massive M. annularis, and fairly extensive areas of A. cervicornis and Porites, and smaller amounts of Millepora and A. palmata. This zone continues round the south end of the reef patch, with scattered colonies of M. annularis.

(b) the reefs along the southern section of the east side: with massive A. palmata, and smaller amounts of Millepora, Diploria, Porites, Montastrea and Agaricia.

(c) the wide area of reef growth in fairly shallow water (less than 10 feet deep) across the northeast end of the reef patch: consisting of massive M. annularis, A. palmata and Millepora, with patches of A. cervicornis (especially in shoal water) and Agaricia agaricites.

(d) the deep-water spurs at the northeast end of the patch, extending down to depths of 20-40 feet, coated with massive M. annularis, together with A. palmata and Porites.

(e) the narrow reef rim on the northwest side of the patch: mainly massive M. annularis, with Mycetophyllia, Isophyllia, Mussa, and on the reef crest, A. cervicornis.

In addition, the centre of the patch, much of it covered with Thalassia, supported scattered small colonies of Manicina areolata, Cladocora arbuscula and Siderastrea radians. Many other species are present in the peripheral reefs (such as Siderastrea siderea, Colpophyllia natans, Dichocoenia stokesii and Dendrogyra cylindrus) but do not in themselves form distinct zones. Thorpe and Bregazzi's full list of species has been given in my previous paper (ARB 87, 17-18).

The changes resulting from the hurricane in these zones may be summarised as follows:

(a) Approximately 80% of the stony corals disappeared in this zone. One patch on the south side of the anchorage gap, consisting of M. annularis, A. palmata and Millepora disappeared entirely. Further south, M. annularis survived in isolated blocks, some of them split apart, together with a little Agaricia. The extensive area of A. cervicornis at the southwest corner has gone entirely, and only scattered Porites porites nestling in cervicornis rubble remain. Scattered colonies of M. annularis along the south side of the reef patch have largely disappeared.

(b) This narrow zone of A. palmata, Millepora, and scattered massive corals (M. annularis, Diploria) suffered very heavy damage, perhaps 90% being destroyed. The chief coral surviving is M. annularis, often with scour holes to leeward of the colonies. Associated with the large surviving coral colonies are a number of smaller corals, including Favia fragum, Mycetophyllia, and Agaricia agaricites. All the A. cervicornis has been destroyed, except for occasional straggling branches rising from blankets of cervicornis debris. Damage to the dominant A. palmata is also great: colonies were broken and overturned, and generally killed, often by smothering with debris, though occasional colonies remained alive even though completely inverted. While previously one could cross this reef at only a few points, it is now possible to swim across almost at will. On the reef flat to leeward, between the reef crest and the beachrock, there are scattered specimens of D. clivosa and

Siderastrea siderea still living, though in some cases overturned. No Porites was seen.

(c) Survival in this zone is much greater, the successful species again being chiefly M. annularis, with the more massive A. palmata, and Diploria. There is much cervicornis rubble, but no living colonies; and no species of Porites were seen except Porites astreoides.

(d) This zone was not examined in detail; from the photographs it is apparent that more coral survived here, possibly because of its greater depth and the dominance of the more resistant species, particularly M. annularis.

(e) Towards the north end nearly all the coral has been destroyed, but elsewhere small colonies of M. annularis have survived. A. cervicornis is not to be seen.

To sum up the reef changes at Rendezvous Reef: Montastrea annularis has survived all round the reef patch with moderate success, together with Millepora, which may, at least in part, have grown since the storm. More massive specimens of A. palmata have also survived in places. On the surface of the patch, Siderastrea radians can still be found in the turtle grass, but not Cladocora or Manicina. The deeper slopes round the whole patch seem to be bare. No large blocks have accumulated in the centre of the patch though the turtle grass is littered with much small debris. As rough estimates of the amount of damage, the total reef damage may be placed at 75-80%; destruction of A. cervicornis 100%; A. palmata 80%; and M. annularis 50%. The extensive rubble banks along the eastern reef crest are now thickly coated with purple algae.

Cay Glory

Damage was also considerable at Cay Glory, 10 miles south of Rendezvous Cay. On the reef flat itself, very little living coral remains, apart from scattered fragments of living Acropora palmata and A. cervicornis. The most widespread corals are now small scattered colonies of M. annularis, P. astreoides, S. siderea, and D. strigosa. Two specimens only of Porites porites were seen, and one of Dichocoenia. The reef crest itself is covered with a fresh rubble carpet 30-40 yards wide, carrying 12 inches of water, with a steep inner margin 2-3 feet high.

Carrie Bow Cay

At Carrie Bow Cay the degree of reef damage has markedly decreased. On the reef flat the reef is healthy but sparse; it includes M. annularis, A. palmata, rather broken A. cervicornis, Agaricia agaricites, Porites porites, Diploria and Siderastrea. The reef crest consists of a rubble carpet 10-15 yards wide, of tightly packed debris, partly rising above sea level, derived from the heavier destruction of corals on the outer slope. Only the upper section of the outer slope could be investigated, where apart from scattered Porites astreoides it is simply a desolate carpet of rubble. Air observation showed that more coral survived at greater

depths, below about 4 fathoms. Furthermore, the massive corals (*Montastrea*, *Diploria*, *Siderastrea*) of the northern and southern horns of the reef survived with little damage.

Peter Douglas Cay

Finally, we may note reef conditions in the central barrier reef lagoon, where destructive hurricane effects on cays were slight, apart from mangrove defoliation. The reef at Peter Douglas Cay consists only of *Montastrea annularis*, *Porites astreoides* and *Siderastrea siderea*, with lesser amounts of *Acropora cervicornis* and *A. prolifera*, and very little *A. palmata*. The only species markedly affected by the hurricane was *A. cervicornis*, the colonies being much broken, but generally still living. No under-water observations were made south of this point, but air observation showed virtually unchanged conditions, both along the southern barrier reef, and on Glover's Reef. A major exception is the reefs round the southernmost islands of the central barrier reef lagoon, where widespread deposition indicates considerable reef damage.

Comment

This catastrophic degree of reef damage over several miles of the barrier reef is of considerable interest. Mortality of corals during storms has previously been described by Moorhouse (1936) following the 1934 cyclone at Low Isles, Great Barrier Reef of Australia, where many branching corals on the reef flat disappeared. Similar, more detailed observations were made at the same place, again on shallow water corals, by Stephenson, Endean and Bennett (1958) following the minor 1954 cyclone. Most observations have been confined to shallow reef-flat and lagoonal waters because of the practical difficulties of investigating the reef-front, resulting from wave action and surf; yet it is on the more exposed reef-front that damage may be expected to be greatest. Thus, following Typhoon Ophelia at Jaluit, Banner reported that "on the bottom of the lagoon below low tide there was no evidence of disturbed conditions. Even delicate corals were not broken. In contrast it seems likely that the outer reef front suffered profound changes", as shown by the amount of fresh coral shingle in bars and shingle carpets (in Blumenstock, 1958, 1269; also Banner, in Blumenstock, editor, 1961, 75-78). Banner's deduction of "rather extensive" hurricane damage on the reef front is born out by the observed changes on the British Honduras reefs, though the evidence of such damage in British Honduras, in the shape of rubble and shingle constructions above sea level, is very much less extensive than on Jaluit.

In general terms, the observation made by Stephenson, Endean and Bennett, and other earlier workers, that the more rapidly-growing, branching, fragile species are more susceptible to damage than the slower-growing, massive, often globular and hemispherical species, is confirmed by the British Honduras data. The most successful coral in resisting damage was everywhere *Montastrea annularis*; the least successful

Acropora cervicornis, Porites other than P. astreoides, and the small unattached corals, such as Manicina areolata, Siderastrea radians, and Cladocora arbuscula. Table 2 lists the more common coral species of the British Honduras reefs in approximate order of resistance to destruction by storms.

Table 2. Relative resistance of species to hurricane damage.

Least resistant	Acropora cervicornis
	Porites porites
	Porites divaricata
	Porites furcata
	Siderastrea radians
	Favia fragum
	Manicina areolata
	Cladocora arbuscula
	Isophyllastrea rigida
	Colpophyllia natans
	Agaricia agaricites
	Mycetophyllia lamarckana
	Acropora palmata
	Siderastrea siderea
	Montastrea cavernosa
	Porites astreoides
	Solenastrea bournoni
	Dichocoenia stokesii
	Dendrogyra cylindrus
	Diploria clivosa
	Diploria labyrinthiformis
	Diploria strigosa
Most resistant	Montastrea annularis

The nature of damage to colonies varies considerably, and some of the more common types of damage may be noted. Acropora palmata is often overturned and even completely inverted, without breakage, and the colony may survive and continue to grow in this way. Examples were seen where new vertical branches were growing upwards from the former undersides of now inverted colonies. Direction of fall of the tree-like colonies is generally from sea to land. Dead Acropora branches are often almost submerged in other debris, which may have been mainly responsible for their deaths. No extensive colonies of A. cervicornis were seen over a 30-40 mile lone reef tract on the barrier reef. The location of former colonies is often marked by piles of broken cervicornis sticks, often tightly packed, with an admixture of other small species. Occasional branches, sometimes broken, may be seen rising from the debris, still with living polyps, but these are uncommon. The most resistant colonies of Montastrea annularis may be rather complex, consisting not of a single hemispherical mass but of numerous smaller sub-hemispherical colonies grouped together in larger colonies with a total height and diameter of several feet, or of a series of overlapping plates also grouped together to form a large colony (Lewis, 1960). Frequently the larger colony has been fractured along the lines of contact between the smaller colonies, and the whole

mass has fallen apart. This type of damage is usually peripheral. Other more purely hemispherical colonies of the genera Diploria, Montastrea, Porites, Siderastrea, Solenastrea, etc., were subject to rolling across the reef flat, some being left inverted but not dead, in the manner envisaged by Kornicker and Boyd for the formation of micro-atolls (Kornicker and Boyd, 1962, 668). These colonies were also subject to wave scour round their margins. Porites porites was several times seen, apparently undisturbed, though no longer living; on examination, however, the colonies proved to be thoroughly shattered and about to disintegrate.

Stephenson and others arrived at similar results in Australia. At Low Isles the more massive and resistant species include Porites lutea, Goniastrea pectinata and Platygyra landlina; the less resistant fragile species included Montipora divaricata and Pocillopora damicornis. While accepting the dominant mechanical effects of hurricane waves, they also draw attention to the effect of increased amounts of debris in the water following the storm; "There is the possibility that destruction of coral may have continued after the cyclone had passed. Moderate and possibly local destruction of Acropora would produce coral rubble whose subsequent movements could damage a much larger area, and would probably hamper recolonisation by corals of areas already devastated. Further degradation into grit would accelerate this process, particularly in a bared area where this grit could be agitated by waves. In 1954 much of the lower seaward slopes of the eastern side of the island was characterised by a substratum of grit and rubble, and the grit was in fact kept in continual motion during moderate seas at low water ... It is not impossible that a really severe cyclone would clear the area more completely of broken coral, and have less prolonged effects" (Stephenson, Endean and Bennett, 1958, 304). The suggestions that increased amounts of mobile debris may help smother still living corals, and that the same debris may also prevent recolonisation, both seem highly probable; on the other hand, even so severe a storm as Hurricane Hattie was insufficient to sweep the debris away, and in this case the effects would seem likely to be more, rather than less prolonged.

Finally, there is the problem of the much greater degree of reef destruction on the barrier than on the outlying reefs. To some extent this is explained by the relative location of reefs and the hurricane track, but there is still a considerable difference between the northern barrier reef and the northern Turneffe reefs. The constriction of the channel between Turneffe and the barrier reef between English and Rendezvous cays, may have led to the piling up of surge water and increased wave action under the influence of northerly winds. On the east reefs of Turneffe there is no such constriction, and adequate drainage to north and south. It is also interesting to note that very little material has accumulated above water level in the area of maximum reef damage. Thus in the case of Rendezvous Cay virtually none of the reef material is now visible above sea level: most of the reef constituents must have been swept into deeper water round the reef patch. On the other hand, where damage was less extreme, as in the southern barrier reef lagoon and in places on Turneffe and Lighthouse Reefs, considerable shingle ridges and carpets have been deposited above sea level. All these extensive depositional features above sea-level, however, lie outside the storm surge zone. Presumably in areas affected by the surge all cay

land was submerged and presented no barrier to the waves, once vegetation had been stripped, whereas outside the surge area, islands acted as barriers to wave movement throughout the storm. To a small extent also the absence of debris above sea level in the surge areas is illusory, as I am informed that much more material was visible immediately after the storm, and has since disappeared through wave action. Nevertheless, it is certain that no features comparable to the great shingle ridges at Jaluit, up to 8 feet high and 20 yards wide, with coral boulders 1-5 feet in diameter, were built anywhere in British Honduras. This comparatively meagre development of ridges on reef flats may perhaps result from poorer reef development in the Caribbean, compared with the Pacific, and the more sheltered sea conditions. At this stage, it might be unwise to attach too great significance to these differences. The subject of sediment deposition is raised again in Chapter 8.

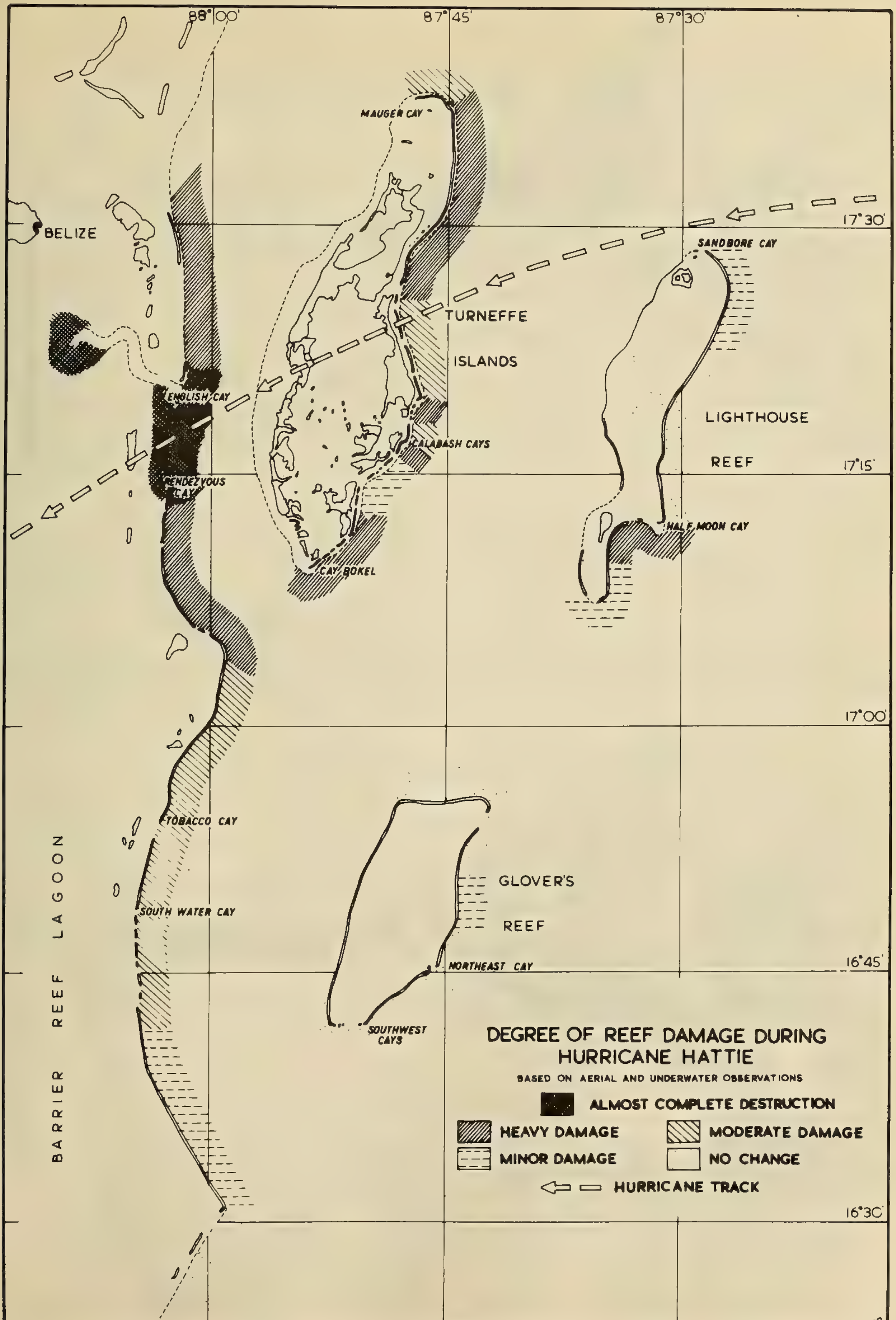

88°00'
87°45'
87°30'
17°30'
17°15'
17°00'
16°45'
16°30'
BELIZE
MAUGER CAY
TURNEFFE
ISLANDS
SANDBORE CAY
LIGHTHOUSE
REEF
ENGLISH CAY
RENDEZVOUS CAY
CALABASH CAYS
CAY BOKEL
HALF MOON CAY
TOBACCO CAY
SOUTH WATER CAY
GLOVER'S
REEF
NORTHEAST CAY
SOUTHWEST CAYS
BARRIER REEF LAGOON
DEGREE OF REEF DAMAGE DURING HURRICANE HATTIE
BASED ON AERIAL AND UNDERWATER OBSERVATIONS
ALMOST COMPLETE DESTRUCTION
HEAVY DAMAGE
MODERATE DAMAGE
MINOR DAMAGE
NO CHANGE
HURRICANE TRACK

FIG. 14

RENDEZVOUS REEF IN 1960
SUBMARINE SURVEY BY J.E. THORPE
YARDS 50
DEPTHS IN FEET
CAY
RENDEZVOUS REEF IN 1962
COLLATION OF AIR PHOTOGRAPHS
CAY

FIG. 15

IV. HURRICANE DAMAGE TO NORTHERN BARRIER REEF CAYS

Hurricane Hattie crossed the northern barrier reef near Rendezvous Cay (Chapter 2, Figure 2), latitude 17°15'N. Damage extended northwards from this point as far as Ambergris Cay and the northern boundary of British Honduras at Boca Bacalar Chico; in this area dominant winds and waves were northwest, north, northeast and east. South of Rendezvous Cay, damage extended almost to Gladden Spit on the barrier reef edge, and almost to Punta Ycacos on the mainland coast; winds and waves were here southwest, south and southeast. Because of this change in wind and wave conditions on either side of the storm track, and because of the number of cays involved, it is convenient to describe those to the north of Rendezvous in the present chapter, and those to the south in Chapter 5. The cays of the southern barrier reef, not affected by Hurricane Hattie, are not considered here and will be described in a later paper. In both chapters the cays are described from north to south.

The general disposition of the cays on the northern barrier reef and in the lagoon has been described by Vermeer (1959, 41-47, 58-65) and will only be broadly outlined here. North of Belize the coastal shelf averages 15 miles in width, and between Belize and the Bulkhead Reef (extending from the mainland to Ambergris Cay) is $1\frac{1}{2}$-$2\frac{1}{2}$ fathoms deep. The Bulkhead itself is a shoal area carrying $\frac{1}{4}$-$\frac{3}{4}$ fathoms, and encloses the 55-mile long Bahia de Chetumal, a drowned portion of Yucatan lowlands carrying 1-3 fathoms, with which we are not here concerned. The cays of the northern barrier are mostly mangrove cays with seaward sand ridges: they include Ambergris Cay, Cangrejo Cay, Cay Caulker and Long Cay. The Hicks Cays are the only extensive group of cays within the lagoon proper north of Belize. Immediately south of Belize the lagoon deepens rapidly to 3-4 fathoms, reaching 10 fathoms in the latitude of Rendezvous Cay. The seaward edge of the coastal shelf is formed by a low platform, 2-4 fathoms deep, 3-4 miles wide, from the outer edge of which the present barrier reef rises to sea level. Several mangrove islands are located on this low platform, including the Drowned Cays, Middle Long Cay and Colson Cays; while a number of small sand cays are found on the barrier reef proper. These include St. George's East Cay, Paunch, Sergeant's, Goff's, English and Rendezvous Cays. South of Belize there are no cays within the lagoon, except for a cluster of mangrove islands with a little dry land at the inner edge of the Deepwater (Grennel's, Eastern) Channel, which intersects the barrier reef and low platform in latitude 17°20'N.

Ambergris Cay

Ambergris Cay is the largest island on the British Honduras coastal shelf, though its description as such is somewhat artificial (Figure 16). It extends for some 25 miles southwards from the Boca Bacalar Chico, a largely artificial channel only 6 feet wide, which gives access from the sea to the Bahia de Chetumal, and serves as the Mexico-British Honduras boundary. The cay varies in width from over 4 miles to less than 100 yards. According to Bird Allen (1841, 80) the cay was named "from the produce of its shores", and Captain Henderson (1811, 24) described it

as "of considerable size, abounding with extensive fresh water lakes, and at most seasons ... plentifully stocked with many kinds of game. This Key is likewise said to produce Logwood, and the more valuable kind of dye-wood, named Brasiletto". Jeffreys noted in his 1775 chart that there were "plenty of deer in it and Ambergrease often found on its Beach".

The seaward shore generally lies ¼ mile from the barrier reef, from which it is separated by a channel 1-2 fathoms deep; but at the rocky Reef Point, 4½ miles south of Boca Bacalar Chico, the shore swings out to the edge of the coastal shelf and the reef itself is interrupted (air photograph in Stoddart, 1960). This is probably controlled by the faulting which has shaped the rectilinear east coast of Yucatan. North of Boca Bacalar Chico the coast consists of uplifted Tertiary Limestones extending to Cabo Chatoche; in the Xcalak area, immediately north of the Boca, the limestones belong to the Carrillo-Puerto Formation of Upper Miocene-Pliocene age (Butterlin and Bonet, 1960). South of the Boca, Ambergris Cay falls into three main divisions: (a) a three-mile long zone of mangrove swamp, lagoon, and tidally-exposed sand; (b) the Basil Jones area, 5 miles long and 2-3 miles wide; and (c) the rest of the cay. The Basil Jones area was briefly visited in March 1960; it consist of a seaward beach ridge and leeward mangrove swamp, with a broad intervening area of palm thicket, distinguished in Figure 16 as high and low woodland with mangrove. Surface bedrock, a creamy limestone, was seen exposed along the track leading to Basil Jones. This is presumably comparable in age to that north of the Boca, and its presence shows that the cay is more properly a long sand and mangrove spit built southwards from a solid rock core, probably continuous at very shallow depths with the main peninsular limestones. "Basil Jones" is the name given to a test drill for oil made in the late 1950's by a Shell-Gulf Oil consortium, which reached 7322 feet without show of oil. No information is available on the well log (Keller and Wories, 1959).

South of Basil Jones is the main part of the cay, extending for about 14 miles. In structure it consists of a seaward sand ridge from 100 to 500 yards wide, backed by a wide zone of <u>Rhizophora</u>. The mangrove often falls into two sections: one immediately adjoining the sand ridge on its lee side, and one two miles to the east, forming the eastern shore of the cay. The intervening area is filled with shoal sand only intermittently colonised by mangrove, and often forming innumerable circular depressions 1-200 yards across, separated by intricate, narrow intertidal sand rims, occasionally colonised by vegetation. These are well developed behind San Pedro, and also near Reef Point; no detailed work has been done on these features, which bear a superficial resemblance to drying patterns in the savanna country near Belize, as seen from the air. The sand ridge is the only dry part of the cay, and is of variable height and width. For most of its length it is only 3-5 feet above sea level, and often lower; but at San Pedro and for about 1 mile to the north it is considerably higher. In 1959 Vermeer described a raised beach on the seaward face of this ridge, 6 feet high and 10-20 yards wide, 2 miles north of San Pedro (1959, 51-52, Figure 6). Levelling in 1961 along this ridge showed variable heights with ridge crests at 5 and 8 feet, and a surface much disturbed by wind erosion and deposition. The tops of the ridges in this area might in fact best be termed dunes under palm thicket. Any such seaward-facing ledge as that described by Vermeer is probably a hurricane

construction (Stoddart, 1962a, 167), and it is in fact doubtful whether any traces of high stands of the sea can be traced anywhere on the British Honduras reefs (ARB 87, 109-110, 123-125). Immediately north of San Pedro village the ridge crest reaches 8 feet above sea level, and the water table, shown by a well, is 7.5 feet deep. The ridge here is about 80 yards wide; on its west side it passes under dense palmetto thicket or Avicennia-Rhizophora bush, depending on altitude. Along the broadly arcuate seaward shore, traces of eroded cemented sands can be found up to 6 inches above sea-level at the promontories separating the bays; these are probably exposures of old cay sandstone, similar to those on the east side of Turneffe. San Pedro village, population about 300 is built on the highest part of the sand ridge, which rises here to nearly 20 feet above sea level. The water table lies at depths of 15-17 feet in wells, and supplies excellent drinking water, which was not contaminated during Hurricane Hattie. Water between the cay and the reef is not less than 1 fathom deep, and the reef itself is poorly developed. In spite of the distance from the storm track, there was considerable erosion of the seaward shore near the village. A number of houses near the sea were undermined by waves and collapsed; the cemetery on lower ground was partly washed into the sea; and a newly-built assemblage of holiday huts south of the village was very badly damaged. Actual retreat of the shore and sand-stripping was, however, minor, and few trees were knocked down. Terminalia catappa was seen living close to the beach, and only the near-shore coconuts were affected by waves. Away from the village, the main effect was deposition of a thin sand carpet a few yards wide. Even at the south end of Ambergris Cay few coconuts have been felled. The limited damage seems to have resulted solely from the work of waves in exposed situations; the wind evidently lacked the force to knock down coconut trees. There is no evidence that the sea crossed the island at any point. Nor is there any evidence of a high storm surge.

The southern tip of Ambergris is formed by a number of small mangrove islands, and between these and the main cay, and also Cay Cangrejo, there are a number of deep submarine channels heading in the shoal reef area and debouching into the main coastal shelf lagoon. Similar channels are to be found between Cay Cangrejo and Cay Caulker. These were photographed before and after the hurricane, and there seems to be no significant change in their form. None of the mangrove on Ambergris is seriously defoliated, except to a limited extent near the south end, and even here Rhizophora on the lee side retains its leaves. The limit of serious defoliation must, therefore, lie between Ambergris Cay and Cay Caulker, about 40 miles north of the storm centre.

The effect of the hurricane on mangrove cays in the lee of Ambergris Cay (Deer Cay, Swab Cay, Blackadore Cay, Mosquito Cay) was negligible.

Cay Caulker

Cay Caulker (Corker of Jeffreys, 1775, and Owen, 1830) is a large mangrove-sand cay situated 5 miles south of Ambergris Cay and 1-1½ miles from the edge of the coastal shelf. It has been briefly described by Vermeer (1959, 55-58). The island, which parallels the shelf edge, is about 4½ miles long, but varies considerably in width. The northern

section, some $2\frac{1}{2}$ miles long, is 350-550 yards wide; then follows a mile-long section, fronting a great leeward indentation, with a maximum width of only some 70 yards; while the broad southern end of the cay widens out to about $\frac{3}{4}$ mile in width (Figure 17).

The island is still very inadequately known; it was visited in 1961 and again in 1962, and photographed from the air in 1959, 1961 and 1962. The seaward side is formed by a sand ridge of variable height. Along the northern half of the cay it is everywhere low, and fronted on the seaward side by now defoliated Rhizophora. Along much of the narrow sector of the cay it is also less than 3 feet high, but near Cay Caulker village it rises to 6-7 feet (Vermeer quotes a maximum of 12 feet). Along the southern section the ridge again declines and is fronted by mangrove. About the interior of the cay very little is known: the southern lobe contains much mangrove and some standing water (Vermeer, 1959, 56-7), and mangrove forms a discontinuous rim round the shore of the main west bay, and also towards the northern end of the west side of the cay. Much of the lee shore, however, consists of a low, often cliffed sand beach without mangrove. The interior of the northern sector is covered with palm thicket rather than with mangrove. The seaward sand ridge is generally planted with coconuts, especially near Cay Caulker village, on the narrow section of the cay.

The village is favourably situated on the highest part of the sand ridge, with an excellent small-boat anchorage in the west bay. It has a population of about 300 and before the hurricane was a boat-building and fishing centre with a largely Spanish-speaking population, a police station and shops. Reyes, Alamina, Young and Bevans were common surnames here. In addition to coconuts a number of other trees were planted near the village, some ornamental (including large specimens of Pinus), some fruit, including mango (Mangifera indica), plantain (Musa paradisiaca), and 'almond' (Terminalia catappa), plus many exotic flowering shrubs.

During the hurricane damage was concentrated near the village itself, where the land, though highest, was narrowest and most cleared of native vegetation. Two streets of wooden houses nearest the sea were destroyed by wave action, together with the main boat-building sites, and the sea completely crossed over the land area at its narrowest point. The schoolhouse, standing in the track of the waves, collapsed, with 14 deaths. At this point, south of the village, the land is low-lying and presented little obstacle. Coconut trees were uprooted, and the holes left by their roots formed the nucleus of scour holes cut into the cay surface. The deepest of these holes is about 6 feet deep and most are about 6 yards long, elongated in the direction of water movement. Further scour holes have been cut in the shallow floor of the west bay close to the shoreline. In the village itself, where the land is higher, east-west trending streets, at right-angles to the shore, channelled storm waters across the cay, and were scoured out to depths of 1-2 feet. The walls of these channels are nearly vertical, and reveal layers of cemented sand, dipping seaward parallel to the cay surface. Elsewhere along the seaward shore there has been stripping of the surface sands within 10 yards of the shore, removing up to 2-3 feet of sand in vertical cross-section, as indicated by the roots of still-standing coconut palms.

The survival of coconut palms, especially away from the narrow area where the sea crossed the island, is remarkable; young trees are still standing within a few feet of the seaward shore itself. Rhizophora has been completely defoliated along the whole of the east shore and along the margins of the west bay; but in March 1962 Rhizophora with leaves was to be seen along the rest of the west shore. Coccolcba survived even near the seaward beach, and Terminalia within 50 yards of it, though both were much broken. One or two large pines were overturned in the village, and there was complete destruction of plantains. Generally, physiographic effects away from the village were negligible, and vegetation damage was moderate, except near the village and along the seaward shore.

Cay Chapel

Cay Chapel (Figure 17) is a mangrove-sand cay lying 1 mile south of Cay Caulker and $1\frac{1}{2}$ miles from the edge of the coastal shelf, here only sparsely fringed with reef. The island is elongate, aligned parallel to the shelf edge; it is $2\frac{1}{4}$ miles long, with a greatest width of about 500 yards. The greater part of the cay is built of parallel sand ridges, aligned north-south rising to a maximum height of 6 feet above sea level. The structure of the ridges and intervening swales has been largely destroyed by bull-dozing operations connected with land clearing. At the northern and southern ends of the cay there is a slight growth of Rhizophora, but otherwise mangrove is restricted to the margins of a leeside swamp area near the middle of the cay. The vegetation of the sand area formerly consisted of a dense palm thicket of coconuts and Thrinax, with Coccoloba, Tournefortia, Suriana, Euphorbia and grasses; it has clearly changed much since Jeffreys noted a single "large cocoa tree" in 1775. Since 1961, however, the island has been in the hands of land developers, who before the hurricane had almost completely cleared the vegetation from the whole of the northern end of the cay, leaving only coconuts standing, with no ground vegetation at all. Previously the island had been exploited for coconuts, yielding 60-70,000 nuts per month. Of the coconuts standing at the time of the storm, residents estimate that 60% were felled; but at the time of my visit most of these had been bulldozed away. In the northern cleared sector there was some undercutting and root-exposure along the east shore, and sand-stripping and root-exposure across a zone about 10-15 yards wide near the shore, and patchy sand deposition across a zone 12-25 yards wide immediately inland from it. The sea is said to have risen to a height of 10-12 feet above normal and to have submerged the northern end of the cay; however, this height is very much greater than that reported for Cay Caulker, and the true rise may have been much less than 10 feet. Since the hurricane, the bare sand surface has been colonised by Tournefortia seedlings, a little Euphorbia and 'burr-burr', Cenchrus.

The southern section of the island is still densely vegetated, and since the hurricane has been almost impenetrable except along bulldozed trails. Wind damage to vegetation has been considerable, acting from the northeast, but maximum damage occurred along the seaward shore, where the vegetation, mostly Coccoloba, has been pushed back for several yards. Immediately south of the easternmost point on the seaward shore, this retreat of the vegetation hedge and the stripping of surface sand has exposed a wide area of cay sandstone. The exposure is about 15 yards square, and dips

seaward. At its outer edge it is 1 foot thick, with its lower edge 18 inches above sea level, at about the limit of normal wave swash. The top of the inner edge rises to about 3 feet above sea level. It is bounded on all sides by steep and overhanging margins, and the surface is deeply pitted and eroded; the surface is also much better cemented than the interior. The constituent sand is very fine, and does not contain the large Halimeda plates and red foraminifera characteristic of intertidal beachrock. Similar cementation can be traced at intervals along the shore beneath the Coccoloba fringe. The exposure seems similar to, though better developed than, that at Cay Caulker village.

Cays between Cay Chapel and Belize

Apart from St. George's Cay and St. George's East Cay, discussed below, there is little to remark about the numerous mangrove islands on the coastal shelf between 17°30'N and 17°45'N. These cays include Long Cay (the northernmost of that name), Hicks Cays, Montego and Frenchman's Cays, Hen and Chicken Cays, Rider's Cays, and the northernmost Drowned Cays. Apart from a narrow seaward fringe of sand and coconuts on Long Cay and on the Drowned Cays north of Gallows Point, these islands consist wholly of mangrove, and are often discontinuous. The Hicks Cays, for example, consist of a dozen islands, four of them large, the intervening passages being shallow and colonised by Rhizophora seedlings, but with deep meandering channels, through which tidal currents set with great rapidity. All these mangrove cays suffered complete defoliation, and most were probably inundated by the storm surge. Flying over them after the storm, the area of bare mud and shallow water within many of the cays seemed greatly increased, probably largely as a result of the breakup of the mangrove canopy; seen in this condition the name of 'drowned cays' seemed particularly appropriate. On the sparse dry areas even coconuts were still standing, but gaps showed that at least 75% had been destroyed. At Montego, Frenchman's, St. George's and Hick's Cays leaf growth on Rhizophora in April, 1962, was limited to young plants on the west sides, indicating protection from easterly hurricane waves.

The form of the Drowned Cays proper is well shown on the new Admiralty chart of Belize Harbour, No. 522 of 1960, based on surveys of 1957-8. These mangrove islands are intersected by a number of narrow east-west channels or 'bogues', namely Shag Cay Bogue, Barrister Bogue, Farls Bogue and Goring Bogue. These are similar to the un-named bogues between Frenchman's, Montego and St. George's Cays further north. Most of these bogues carry 3-4 fathoms water, and they must have acted as major drainage channels for the east-west passage of water during the storm surge. The northernmost bogues show signs of scouring, with prominent sand deltas at their western end (e.g. north of St. George's Cay) but there is no means of estimating the amount of deepening either here or at Drowned Cays.

Stake Bank, midway between Drowned Cays and Belize, is worthy of mention. According to Anthony de Mayne's MS survey of Belize Harbour, 1828, this was at that time a shoal bank with one or two mangrove seedlings. There is a widespread tradition that the shoal is built from ballast deposited by ships in the harbour (Anderson, 1958, 95). In 1765 Speer described it as a "long Bank, ... called Stake Bank, ... dry in some parts";

it was not then visible until close by, as Speer gives course directions when it may be seen "if you look out well" (1765, 20). Jeffreys marked it on his 1775 chart. Since 1828 the few mangrove seedlings have expanded to form a mangrove cay 500 yards long, resting on a shoal measuring approximately 2000 x 1000 yards.

A further point of interest concerns the coastline near Belize. Immediately south of the Belize River peninsula, in Sibun Bight, vertical air photographs flown by the R.A.F. after the hurricane (V2/543/RAFI565/0071-72, 17 December, 1961) compared with the U.S. Navy cover 1945, reveal scour and bottom deepening between the coast and the three-fathom line. The scour hole, which follows the curvature of the coast, is 2000 yards long and averages 1100 yards in width. Unfortunately it was not seen while in British Honduras, and was not investigated in the field.

For further notes on the Drowned Cays, see Vermeer (1959, 58-59).

St. George's Cay

St. George's Cay deserves fairly detailed treatment, not only because of the extent of the hurricane damage, but because of the island's importance in the history of the Colony. According to Romney and others (1959 , Figure 10) there is a Maya shell-midden on the cay; but its importance really dates from the European occupation. The Spanish knew it as Cayo Casino, but the name changed after the English took it over in the late seventeenth century. Captain Henderson spoke of it as

> "a most agreeable and healthful spot, ... which contains a number of good houses. This is much resorted to as a place of convenient retirement by the inhabitants of the settlement during the hot months. The purity of the air and other advantages connected with it render it likewise a desirable retreat for the sick and convalescent. Some years past, St. George's Kay was the chief place of trade in this part of the world, on which the merchants almost wholly resided; and where the vessels engaged in it deposited their cargoes and again took in their lading." (1811, 22-23).

The Honduras Almanack for 1829 gave a fuller description (13-14):

> "St. George's Kay, is very narrow in some parts, and about one mile in length, in the shape of a crescent, at the northern extremity. It is now chiefly used as a place of retirement from the bustle of business, and the peculiar salubrity of the air renders it highly beneficial to invalids, and convalescents, particularly in the hot months. Here is a Government House, for the Superintendant, besides many other good and substantial buildings. On the western side there is a commodious situation, called Irish Bay, where Droggers and smaller crafts are built, and repaired. Off the Eastern side of

> the island, vessels of large burden are still loaded for the European markets, with mahogany from the New River, and its vicinity. ... The soil is naturally sterile, though at some labour, and expense, small gardens have been successfully cultivated upon it."

In the later eighteenth century, however, the focus of government was already moving to Belize. In 1798 all the houses on the cay were destroyed by the settlers a short time before an attack by the Spanish. In the ensuing "Battle of St. George's Cay" of 10 September, 1798 the Spanish were repulsed, and this has been held, incorrectly, to give the English title to the whole of British Honduras by right of conquest (Anderson, 1958, 36-39; Carr and Thorpe, 1961, 46-47, 169-170; Humphreys, 1961). In the early part of the nineteenth century a Government House, Cathedral and Barracks were all built in Belize, and the island became simply a holiday resort, a function it continues to fulfill.

The cay is situated (Figure 18) a little more than $1\frac{1}{4}$ miles from the edge of the coastal shelf, to the north of a broad shelf-edge embayment carrying 4-6 fathoms of water. It lies to the south of an extensive group of small mangrove islands, extending from Hicks Cays to Frenchman's Cay, which have increased considerably in area since Owen's survey in 1830; and about $2\frac{1}{4}$ miles to the north of Drowned Cays. The island itself is crescentic, convex to the southeast, with a total length, measured along its seaward shore, of nearly two miles. It falls naturally into two parts: the southwest section, which is fairly straight, about a mile long and 100-200 yards wide, and consists entirely of mangrove, with little if any dry land; and the northeast section, recurving at its north end, also about a mile long measured along its seaward shore, low, sandy, and inhabited. The Rhizophora section will not be further discussed, except to say that with the exception of defoliation it suffered no considerable changes during Hurricane Hattie.

The sandy section was visited in February, 1960, and photographed from the air in 1961. It then consisted of an arcuate strip of sand varying from 100 to less than 50 yards in width, generally about 1 foot above sea level, rising a little higher in a few places, falling rather lower in others. About one half of the seaward shore was protected by a low masonry wall. The leeward shore, facing what used to be known as Irish Bay, had much mangrove towards its north end, with a few isolated islands of mangrove in the bay itself. The vegetation of the sandy area was highly artificial; houses had been built along its whole length, and coconuts had been planted for shade. The ground vegetation consisted chiefly of grasses, Sesuvium, Euphorbia, Ipomoea, Lobelia and similar plants. There were a few Coccoloba trees, and numbers of cultivated plants, including fruiting plants, in the house gardens. Because of the amount of human interference, however, no collections were made.

Damage during the hurricane was intense (Figure 19). All the 27 jetties, most with enclosed swimming pools or "crawls" at the end, were destroyed, though their positions can still be clearly seen in bottom weed patterns, and only some half dozen houses remained standing, all of them badly damaged. The damage may be described in two parts, occurring north and south of Channel A. North of this point the cay is

generally 100 yards wide, with extensive mangrove on its lee shore; the seawardshore, facing north, northwest and northeast, is protected for nearly all its length by a masonry wall. On the north and particularly northwest-facing sections, damage was not catastrophic. Some houses and many coconuts stood, and the original ground vegetation of Paspalum, Euphorbia, Wedelia and Hymenocallis survived. Apart from the few houses which remained standing in the northwest-facing section, buildings disappeared entirely, except for concrete foundations, and such things as concrete vats. All crawls disappeared. Direction of tree fall varied from 225-250°, and may reflect wave action as well as northeasterly winds. The number of fallen trees increases southwards, until near Channel A almost all trees have disappeared. The masonry wall protected the shore to some extent, but it is now separated from the shore by 2-3 yards of water along most of its length. In places the wall itself has been broken up and has disappeared.

The second section, about 750 yards long, is much narrower, from 45 to 70 yards wide, and lacks any mangrove on its lee shore. It is very low-lying, protected by a wall for only part of its length, with a number of Rhizophora bushes between the crawls on the seaward shore. The vegetation had been almost entirely removed for large, closely spaced houses, with crawls, and the vegetation was restricted to a few coconuts and a sparse ground cover. Of the houses, only the remains of three can now be seen, but of these one is strangely almost undamaged; many people sheltered in it during the storm. The whole of this section of the cay must have been submerged during the hurricane. The most distinctive features of damage are the five channels cut across the island, four of which are deeply scoured. Channel A is the most northerly and largest; it bifurcates seawards, and passes seawards into a large submerged sand delta on the seaward side. On its north flank there is a very deep circular scour hole cut by the side of a concrete tank. The channels and scour hole are both more than 20 feet deep. Between Channels A and B the cay surface lies only a few inches above sea level, and has been cut into a number of irregular sections, separated by water at high tide: the intact house stands on one of these. Channel B is smaller, with no delta, but deepens and widens seawards. Patches of grass have survived in places between the two channels. Between Channel B and C the cay segments are larger, also with some grass, but all the houses and nearly all the trees have disappeared. Channel C is narrow (about 10 yards wide) but at least 3 fathoms deep; it too has a large delta on its seaward side. Between Channels C and D the sand surface is higher, with a number of coconuts and some Coccoloba standing, a surviving ground cover of grasses, Wedelia and Hymenocallis, and some dead Rhizophora on the seaward shore. At its southern end is the cemetery dating from the earliest days of the colony; it has been much broken and only two or three stones are now decipherable, one dating from 1836. Fortunately the inscriptions have been published (Usher, 1907). Channel D, 20 yards wide, and Channel E, 25 yards wide, also contain fairly deep scour holes, both probably more than 2 fathoms deep, with large sand deltas at their eastern mouths. South of Channel E there is but a small sandy area before the cay passes into the main mangrove sector. Fallen coconuts on this sand area are aligned 225-260°, apparently in response to northeasterly winds, but the presence of scour holes filled with water, often at the base of fallen trees, and a thin, dis-

continuous fresh sand carpet, show that the surface was submerged. Patterns in the sand carpet also indicate northeasterly waves. Much wreckage has been piled against the mangrove itself. The ground vegetation has survived fairly well in this section, and consists of grasses, Ageratum, Cakile, Euphorbia and Cyperus. The fresh sand is now being colonised by Sporobolus. All the Rhizophora along the west shores of the sandy area is completely defoliated, and in March, 1962 had not begun to regain leaves.

The two main conclusions from this account of St. George's Cay are, first, that destructive winds and waves, shown by coconut trees, accumulations of wreckage, and sand patterns, came from the northeast; and second, that the channels which intersect the cay, as shown by their deltas, were cut from Irish Bay toward the sea, that is, from the northwest. In Chapter 2 it was shown that west and northwest winds immediately preceded the arrival of the storm centre, so that the channels may have been cut before the other features ascribed to northeasterly winds and waves. The freshness of the sand deltas, however, argues against this.

In early 1962, parties were continuing to visit the island for recreational purposes, generally making day trips from Belize, even though whatever advantages the island previously enjoyed (cf. Carr and Thorpe, 1961, 47) had been completely destroyed.

St. George's East Cay

St. George's East Cay (Figure 20) was, before the hurricane, a small island on the northern side of the major reef gap between Gallows Point Reef and St. George's Cay. It was situated on a small patch reef, 1¼ miles due east of St. George's Cay itself. Owen did not chart it in 1830, and it does not appear on any subsequent Admiralty charts. In 1960 it was the most northerly of the true sand cays on the barrier reef; it was photographed from the air in 1961.

In 1960 the island was crescent-shaped and convex to the northwest, with a greatest length along its main axis of 120 yards. The island was formed by a ridge of medium shingle along its northwest shore, rising steeply to 3 feet above sea level. From the crest line the surface sloped gradually to the southeast. At each end of the cay the shingle formed flat-topped lobes, enclosing a sandy beach along the southeast shore. The shingle consisted largely of Acropora fragments 3-6 inches long; but on the island surface recognisable coral fragments were fewer, and coarse sand predominated. Water more than 1 fathom deep approached within 2 yards of the northwest shore, and the bottom near the island was cobble covered.

No trees grew on the cay, which was consequently inconspicuous. Much of the ground surface was covered with a discontinuous mat of Sesuvium portulacastrum, interspersed with patches of Euphorbia mesembryanthemifolia and clumps of Tournefortia gnaphalodes. Over the southwest two thirds of the cay these were virtually the only plants to be found, together with a single Rhizophora seedling. At the northeast end the vegetation was more luxuriant: a ground cover of Sesuvium, Canavalia and Ipomoea, with

bushes of Tournefortia, Conocarpus and Borrichia up to 4 feet high. The cay was not inhabited, and did not appear to be often visited, which probably accounted for the unusual development of vegetation on a sand cay so near to Belize.

During Hurricane Hattie the cay was completely washed away, and no sandbore or shoal could be seen on the site of the old island in April, 1962. St. George's East Cay was the largest sand cay to disappear entirely during the storm.

Paunch Cay

Paunch Cay, the Punchgut Kay of Speer (1771) and Paunchgut of Jeffreys (1775), was located in 1960 on a small reef patch on the coastal shelf edge, near the southern end of Drowned Cays. It was then 50 yards long and 10-20 yards wide, and consisted of a strip of coarse white sand with a little shingle, elongated north-south. The island was asymmetrical, with a pronounced ridge rising to 3 feet above sea level along the west shore (Figure 21). Three parallel and slightly submerged lines of beachrock were seen off this side of the cay, trending slightly west of north. The longest extended for 50 yards, passing southwards under cay sands; all the lines were broken and interrupted, but clearly dipped to the west. The surface of the rock was thickly covered with algae and some small living corals, including Favia, Siderastrea and Porites. The surface was irregular and eroded, and the rock was cavernous underneath, sheltering many crayfish.

The island was then unvegetated: it had a plant cover during Owen's 1830 survey, and in 1896-7 the Rambler noted huts and palm trees 35 feet tall. This vegetated island was destroyed in the hurricane of 10 September, 1931; the relict beachrock now visible may date from the pre-hurricane cay. Between 1931 and 1961 Paunch Cay was simply a shifting unvegetated sandbore, on the site of the older island. During Hurricane Hattie the sandbore itself was washed away, and much of the living reef destroyed. After the storm the beachrock remained in place but seemed more broken. All larger algae and small corals had been swept from its surface; only one Halimeda plant was seen, no crayfish and few sea urchins. In the area of the old cay to the east of the beachrock, the floor now carried 2½-3 feet of water. A few yards east of the beachrock a steep-sided rubble patch rises to within 12-15 inches of the surface, and consists mainly of cervicornis debris, tightly packed. It seems likely that a new sandbore based on this post-hurricane shingle foundation will shortly emerge, forming a fresh sandbore comparable to that existing between 1931 and 1961.

Sergeant's Cay

Sergeant's Cay (sometimes spelt "Serjeant's")(Figure 22) is situated on a reef patch at the edge of the coastal shelf, one mile south of Paunch Cay; it was charted by Speer (1771) and Jeffreys (1775). At the time of the Rambler survey in 1896-7 it had "huts and palm trees" with "tops of trees about fifty feet"; and this description appeared on charts until the Vidal survey of 1957-8. Until the 1961 hurricane it remained a tolerable description of the cay.

Before the storm the island was roughly triangular, with a greatest length of 110 yards along the south side, and a greatest width of 50 yards. There was little variation in surface level, which reached 2-3 feet above sea-level, but the western shore was cliffed and undercut. In February 1960 there was an accumulation of fresh sand along this side of the cay, forming promontories to northwest and southwest. This undercutting and subsequent accumulation was noted in mid-1957 by Vermeer (1959, 73); but his estimated height of 5 feet on the windward shore is much exaggerated (Vermeer, 1959, 71-74). The total area of the cay in 1960 was approximately 4500 sq. yards, of which the fresh sand area on the west side accounted for 11%. The cay stands on a small reef patch, with a shallow reef flat along its seaward shore. The southern shore shelved steeply to depths of 1-1½ fathoms, giving anchorage to small boats and access to a substantial wooden pier 60 yards long. About 10 yards from the shore itself there was a submerged barrier of conch shells which did not quite reach the surface. The vegetation of the island was completely artificial. With the exception of a large *Avicennia* on the south shore, the only trees were some three dozen coconuts, with no undergrowth. The island was privately owned by an American fishing syndicate, and had a large clubhouse, two smaller houses, and three water tanks. No beachrock was exposed round the cay.

During Hurricane Hattie Sergeant's Cay was almost completely destroyed though fortunately the inhabitants had taken refuge on the larger Water Cay and no-one was killed. Pilots from English Cay who sailed past Sergeant's on 4 November, 1961 report that the cay was then completely awash, with waves overtopping a low sand shoal. In March 1962, when the re-survey was made, however, a sizeable island had again grown up, and plant colonisation was beginning. The only traces of the former cay were a tilted concrete water tank on the east shore; house posts and concrete rubble some yards to seaward; posts from the demolished jetty on the south shore; and a small area of coconut roots near the centre of the island. These traces permit the fairly precise location of the present cay with reference to the old on Figure 22. The new island has an area of 2600 sq. yards, a decrease in total area of rather more than two-fifths. The highest point on the cay is about 3 feet above sea level on the north point, where sand and shingle forms a crescentic ridge. There is some undercutting near the west point, forming a steep sand cliff 2½ feet high. The main plant coloniser is *Portulaca oleracea*, in scattered patches 1-2 feet in diameter, with thick succulent leaves and stems and yellow flowers. Two other species were present in small patches: *Sesuvium portulacastrum* and *Euphorbia mesembrianthemifolia*; near the centre of the cay there is a single small *Rhizophora* seedling. It is unlikely that the cay will again be settled in the near future, and it will be interesting to follow the evolution of the island and its vegetation. North of the island the shallow sea floor is covered with *Thalassia* turf dating from before the storm; this is almost undamaged, except for a number of shallow round scour holes cut through to the underlying sand.

Goff's Cay

Goff's Cay (Figure 23) is located on the northern side of the entrance to the Deepwater Channel, at the south end of a strip of surface reef, trending N-S and about 800 yards long. Bottom topography near the cay is intricate as a result of former karst erosion at the edge of the coastal shelf; the shelf itself near the cay carries 1-2 fathoms of water, but immediately east and south there are deeper channels and holes with up to 24 fathoms. The edge of the shelf (50 fathom isobath) lies about 1100 yards east of the cay. Before the storm the island itself was triangular with sides 70-80 yards long, and straight shorelines. The whole cay was built of rather gray sand, with no shingle. In February, 1960, and on later occasions, there was an extensive spit, 20-25 yards long, of fresh white sand, unvegetated, at the north end of the cay. A smaller, similar spit was mapped at the southeast corner. The shore of the cay behind both spits was undercut. No beachrock could be seen round the shores. The reef flat to the east of the island was narrow, about 25 yards wide, and scattered with algae-blackened boulders and fragments of coral. Coconuts dominated the vegetation and formed a canopy over the central island-core. There were several trees of Coccoloba uvifera, and several small Avicennia trees on the southeast side. At the northeast end of the cay, beginning to extend across the fresh sand accumulation, was a crescentic mat of Sesuvium, with some Ipomoea and Canavalia, giving way inland to a narrow patchy zone of Euphorbia mesembrianthemifolia. Most of the surface under the coconuts was bare sand, with only long straggling vines of Ipomoea and Canavalia and some Euphorbia.

Speer (1765, 19) referred to it as a "small round Kay ... not so big as English Kay", and Jeffreys (1775) charted it as 'Gough's Cay'. In 1896-7 the Rambler noted "huts and palm trees", with "tops of trees about 45 feet high". Since that time there was little apparent change until the 1961 hurricane.

During the storm the core-island suffered severe marginal erosion, decreasing in area by nearly 60%, from 2100 sq. yards to 950 sq. yards. The two sand spits mapped in 1960, covering 1100 sq. yards were completely washed away. Immediately after the hurricane it is clear that the cay had decreased to two-sevenths of its former size. In March 1962, however, at the time of the re-survey a considerable amount of fresh sand had accumulated round the old eroded core, adding some 1700 sq. yards to the 950 sq. yards left by the storm. The total area had thus increased to 80% of that before the storm, though a much greater proportion consisted of fresh loose sand rather than root-bound core.

The remnant of the core-island has been stripped of surface sand, and coconut roots are exposed. Its margins are undercut, steep, and formed of roots from which most of the sand has been flushed. Rocks and rubble are piled against the southeast shore. The reef flat to the east is covered with rubble and shingle, forming in places a continuous carpet of imbricated slabs. Rubble forms a broad zone along the reef crest, breaking surface at several places to form exposed shingle ridges less than 2 feet high. Some 400 yards north of the cay a circular sandbore of variable diameter was seen several times where no sandbore had pre-

viously existed. Two new exposures of beachrock were uncovered off the south and east shores, to seaward of the old cay site, dating from a period when the cay stood farther southeast than now. The exposures are flat-lying and show no clear dip. Before the hurricane they were presumably covered with sand.

Some broken vegetation survives on the island, nearly all of it dead. There are two or three coconuts, and a few much broken but still recognisable Coccoloba. The foundation posts of the hut can be seen near the southeast shore. The only new plant coloniser at the time of my visit was Portulaca oleracea, in a few scattered patches.

One point of interest, which shows that the cay has not materially shifted its position in the last century, is of a somewhat macabre nature. At the time of the first Admiralty survey of this coast, yellow fever carried off an officer and eleven men on the survey ship, and they were buried on Goff's Cay, a fact recorded on a plaque in St. John's Cathedral, Belize. In March, 1961, a number of skeletons, presumably of these unfortunate persons, began to wash out of the cay on its south side. Mr. A.H. Anderson, Archaeological Commissioner, collected the remains and took them to Belize, where they were found to include both male and female bones.

English Cay

English Cay (Figure 24) is located on one of a number of patch reefs on the south side of the entrance to the Deepwater Channel, three miles southwest of Goff's Cay. It was charted by Speer in 1771 and Jeffreys in 1775, and has played some part in the history of the Belize settlement. Speer (1765, 19) termed it "a short, round, bluff Kay", and the description still holds. Before the hurricane the island was triangular, with sides 80-100 yards long. Both the northwest and south shores were slightly undercut, and marked by leaning and fallen coconut trees. The third shore, facing east, was largely artificial, being formed in the north by a masonry wall and farther south by a rampart of conch shells. The island was low and sandy, rising to 2-3 feet above sea level on its east shore, and to approximately 4 feet above sea level in the cay centre, near the lighthouse base. The cliffed shores to northwest and south were 12-18 inches high. The cay was composed entirely of fine sand with no shingle. In January 1960 there was a large fresh sand lobe at the southwest corner, projecting some 30 yards from the island core. This was seen on several other occasions, and was clearly a temporary and fluctuating, perhaps seasonal, accumulation. Vermeer, in a brief description of English Cay, says of it: "A sand spit which curves round toward the east, extends from the southeast part of the cay. Observed on my first visit to the cay, the spit had been washed away and was nothing more than a shoal bank of sand on a return visit some two months later" (1959, 75); this was in 1957. No beachrock was visible round the island.

The cay is a pilot station, and has a lighthouse 60 feet high, built in 1935, together with the remains of an older fixed light. There was a considerable semi-permanent population, and nine houses. The natural vegetation had been almost entirely removed, and the cay supported only

coconut palms, particularly on the east side, where they were planted in regular rows. On the east shore near the conch shell rampart there were also two old and moribund specimens of Rhizophora, standing some yards inland from the shore, toward which they had apparently grown in step-by-step fashion. There was a single specimen of Coccoloba uvifera on the south shore. Coral was awash on the east and south sides of the reef patch only 40-50 yards from the cay, across a reef flat 1-2 feet deep. On the west side, however, there was an anchorage in 1-2 fathoms water over a sandy Thalassia-covered bottom, giving access to a 60 yard long jetty.

English Cay was severely damaged by Hurricane Hattie. All the houses, and all except 8 of the 98 coconut trees disappeared from the cay. Most of the remaining coconuts lost their crowns. The lighthouse stood, as did a steel water tank; a water mark on the side of the tank showed that the sea had risen during the storm to a level approximately 12 feet above normal. The remains of the original lighthouse had been dismantled in mid-1961, before the hurricane struck. The concrete wall and conch shell rampart were unable to protect the seaward shore: the conch shells disappeared, and only fragments of the wall remain. The east beach retreated 5-10 yards along its whole extent; at the north end of the cay a triangular segment of land of some 575 sq. yards was eroded away; the fresh sand lobe at the southwest corner disappeared; and the south and northwest shores also retreated from 2-10 yards. Rough calculations show that of an original area of 5750 sq. yards, 3150 sq. yards remain; one-third of the original land area has disappeared. However, most of this lost area is accounted for by the disappearance of the large fresh sand lobe, so that the erosion of the island core was nearer to one-sixth than one-third. Coconut roots were exposed along the whole of the east shore, but over the cay surface there has been surprisingly little sand-stripping and root-exposure. Residents informed me that immediately after the storm there was much rubble and coral debris strewn over the cay surface, together with fallen tree-trunks and other material, but in March 1962 nearly all this had been cleared, in some places forming a bank round the shore. It is interesting to note that the straggling Rhizophora seen before the storm survived, but now stands several feet seaward of the shore. Only the broken trunk of the Coccoloba remains. Houses are already being re-erected on the cay, which because of the pilot station and lighthouse had to be re-occupied within a few days of the storm. Water supply proved the greatest difficulty, as there is no fresh water lens and the vats were full of seawater, but this is only a temporary difficulty. It was also interesting to note the reappearance of a fresh leeward sand spit; when the cay was remapped in March this was not to be seen, but a few days later a long sinuous spit 50 yards long extended westwards from the western point.

The Southern Triangles

The Southern Triangles is a convenient name to apply to the two clusters of islands at the inner end of the Deepwater Channel (Figure 25). The name has of late fallen into disuse, though the cays on the south side of the channel are still named "The Triangles" on charts, those on the north side being given no specific name. In the eighteenth century, however, the whole group was referred to as the Southern Triangles, both in

the Anglo-Spanish treaties of 1753 and 1783, and on the charts of Jeffreys (1775) and Speer (1765, 1771). The group contains some two dozen islands, mostly mangrove, situated on the flat tops of steep-sided shoals rising abruptly from 5-6 fathoms. The Deepwater Channel (Southern Grennels Channel) between the two clusters of cays has depths of 10-13 fathoms and very steep sides.

The northern group includes seven large islands including Ramsays Cay, One Man Cay, Robinson Island, Grennels Cay, and Robinson Point. Robinson Point Cay is the largest after Robinson Island, and the only one inhabited before the storm; it has a lighthouse erected at its westernmost point in 1939 (Figure 26). Vermeer discusses this island (1959, 75-79) and gives a fine air photograph (his Figure 16) which shows very well the general form of these cays. Robinson Point Cay is about ½ mile long, and consists of a low, narrow sand ridge on its west and southwest sides. The easternmost part of the cay, and most of the area lying to the north of the sand ridge, is covered with Rhizophora and shallow open water. The sand ridge is nowhere more than 50 yards wide, and is generally much narrower; before the hurricane it carried a dense vegetation of coconuts, palmetto, exotic ornamental plants, and such typical strand species as Coccoloba uvifera, Cordia sebestena, Suriana maritima, Conocarpus erectus, Hymenocallis littoralis, Euphorbia sp., Stachytarpheta jamaicensis, Cyperus planifolius and grasses. In places, clumps of Rhizophora are found growing on the exposed south and southwest shores. Vermeer made much of the fact that the dryland area consisted mainly of shingle rather than sand, in contrast to other sand-mangrove cays such as Cays Caulker and Chapel. He noted the dominance of cervicornis debris, but his deduction that Acropora "is restricted to deeper water and does not usually live in more exposed parts of the reef" (1959, 77) is not acceptable. Cervicornis shingle ridges associated with mangrove are in fact fairly widespread in the barrier reef lagoon, the cervicornis flourishing in fairly sheltered water, and such ridges are not restricted, as Vermeer supposed, to deep water areas such as the margins of the Deepwater Channel. The shingle ridge at Robinson Point Cay does not rise more than 3 feet above the sea and is generally lower.

The sketch map of the cay (Figure 26) is not based on ground survey, but on an enlargement of the 1957-8 Vidal survey fair copy chart (Admiralty MS K2254), with detail added from my own air photographs and ground observations in 1961. The shingle-sand area with palm thicket is arcuate, with the lighthouse at its western point, and is about 1000 yards long. Immediately to the lee is an enclosed area of shoal water and bare mud, scattered with Rhizophora seedlings and enclosed by mature Rhizophora. The eastern 800 yards of the island consists of mature Rhizophora and Avicennia, and the ground surface here is generally above high tide level. In 1961 the cay was inhabited: three of the four dwelling houses were occupied, and there was a boat-building shed and slipway still in working order. Few boats had been built there for many years, however, in contrast with the thriving business at Cay Caulker and in Belize; though the island has a history of boat-building dating back at least to the early eighteenth century. The inhabitants were of interest: they were white settlers of English descent, whose ancestors had emigrated from Bath to the Mosquito Shore in the nineteenth century. They still spoke fine English, though with accent and expressions characteristic of the old English colonies of the Western Caribbean.

During Hurricane Hattie the island suffered great damage, and was completely submerged by the storm surge. All the houses and the boat shed disappeared, but the lighthouse survived. The inhabitants, all in Belize at the time of the storm, have now emigrated to the United States, and the cay is deserted. The lighthouse is automatic and is serviced from Belize, and thus requires no resident staff. All the dense vegetation was stripped from the shingle area, except for a few still-standing coconuts. Rhizophora round the cay margins was completely defoliated, and the more exposed trees were also broken up, losing their branches. In May 1962 the mangrove was again bearing leaves in the sheltered centre of the eastern mangrove area. The sand ridge immediately south of the lighthouse was almost breached, but otherwise there was little alteration to the cay outline.

Precisely similar damage was suffered at Robinson Island. The palm thicket was largely stripped, and the exposed Rhizophora was defoliated and broken. In the interior, however, and along the northwest-facing shore, the leaves are beginning to grow again. The implication is that heaviest waves came from the direction of deepwater east and southeast of the cay in the Deepwater Channel. The other islands in the northern group are all mangrove, and damage was comparable to that in the mangrove sections of Robinson and Robinson Point Cays.

The southern group of cays are all mangrove, with the exception of the easternmost, Spanish Cay. One can say little about the mangrove cays (Simmonds, Crayfish, Long and other cays), except that they consist of now defoliated Rhizophora on small shoals. Spanish Cay (Figure 27) is of more interest; when mapped in 1961 it was about 110 yards long and varied from 10-20 yards in width. The surface was low-lying and in places marshy, and consisted of a coarse sand with much Halimeda, scattered coral fragments and conch shells. The southern end of the cay was fringed with tall Rhizophora - remnants of a probably once more extensive cover - and there were numbers of tall Avicennia trees in several places. The vegetation had mostly been replaced by scattered coconuts, with Conocarpus bushes, grasses and sedges, and some ornamental plants. The island was used largely as a holiday resort: it had two very substantial houses, a number of huts and water tanks, a tomb, and two decrepit jetties; and it was divided across the middle by a fence. After the hurricane Spanish Cay was photographed from the air, but not visited. The jetties, huts, and all but one house had disappeared, together with most of the coconuts and nearly all the Rhizophora and Avicennia. The cover of grasses and sedges remained, however, at the north end, where old paths could be clearly traced. There had been slight shore erosion on the east side and signs of deposition along the west shore. The fact that any vegetation survived contrasts with other cays of similar size on the barrier reef itself in the same latitude.

Rendezvous Cay

Damage on Rendezvous Reef has already been outlined (Chapter 3); damage on Rendezvous Cay was less catastrophic, but still severe. The cay (Figure 28) is situated near the south end of the reef patch, and is also oriented N-S (cf. Figure 15). In plan it is rather intricate, but may be described in a generalised way as a very slightly arcuate strip of

sand, convex to the east, with a total length of some 100 yards, and a width varying from 10 to 25 yards. Before the hurricane the western bay was partly filled in with a number of conch shell projections, built over a number of years in the 1920's and 1930's by a fisherman who made the cay his home; the cay was at this time known as "Brown's Cay", after this gentleman, and the name is still used among the older fishermen of the area. In 1960 the cay extended southwards by a narrow, tombolo-like sandspit to another island of conch shells 10 yards long; but this link did not exist in 1959. The cay itself was entirely composed of sand with much Halimeda. On the west side before the storm a beach ridge running the length of the cay rose to a maximum height of nearly 3 feet above sea level, but the greater part of the cay surface maintained a uniform elevation 1½-2 feet above the sea. There were scarcely perceptible ridges round the north shore of the cay. Northwards the cay was extended by a submerged shoal along the centre of the reef patch; the shoal consisted of sand, calcareous mud and such smaller debris as shells, small corals and branching calcareous algae. This spit was occasionally exposed at exceptionally low tides for a distance of about 50 yards. No beachrock was seen round the present shores, but there is a single arcuate line on the reef flat east of the cay, at distances of 30-40 yards from the shore. The rock is cavernous, and the exposure is fragmentary; only the southern section shows any seaward dip. It rises from water 12-15 inches deep, and before the hurricane was thickly covered with larger algae. The exposure has a maximum width of 2 feet at the south end; towards the north it is seen only as a bare strip in the thick Thalassia, though rock is revealed by auger probes.

Speer and Jefferys both charted the cay in 1771 and 1775 respectively, and Speer described it (1765, 19) as "a low sand Kay, with only one bush on it". Owen charted it in 1830 without comment, but by the time of the Mutine survey in 1921-2 it had huts and palm trees 45 feet high, and was conspicuous. Since that time much of the conch shell area has been added, and in recent years the island was purchased by the Governor of the Colony, who built a house and jetty there. Before the hurricane the vegetation was extremely restricted. At the north end and on the east shore were one or two rather gnarled mature Avicennia trees, and scattered over the cay were a number of rather low and stunted Coccoloba trees. Apart from these the vegetation was limited to coconuts, varying in height from 15 to 60 feet; numerous Rhizophora seedlings, especially on the west shore; and very sparse patches of Sesuvium, Euphorbia, and Sporobolus, all frequently cleared.

The island suffered considerable damage during the storm. The house completely disappeared, except for the foundation stones; one of the concrete foundation stones was subsequently found on the eastern reef-crest, 100 yards northeast of its original location, others were found in shallow water off the southeast shore. All the coconut trees were destroyed, and only a few stumps remain near the centre of the cay. The two jetties (one of conch shells, the other timber) were destroyed, though the conch shell one can still be traced for some yards underwater. The seaward shore suffered remarkably little erosion, and roots are exposed only at one point. Much sand was deposited on the west side, however, especially on the conch shell areas, which were much disturbed. The spit between the cay and the small conch shell island to the south was destroyed. There was some surface stripping of sand, particularly at the northern end,

where the surface now sinks to an enclosed, ill-drained hollow. No fresh beachrock was exposed, nor was the old relict beachrock damaged, apart from the stripping of large algae. Much sand has accumulated on the submerged northern spit, which now almost breaks surface in several places, even in normal tides. The total area of the cay has changed little: before the storm it totalled 2800 sq. yards, of which nearly 400 sq. yards was composed of conch shells, many much rotted and rising only 6-12 inches above sea level. The present area of sand is 2400 sq. yards, the same as before, but the conch shell area has been decreased by nearly half to 220 sq. yards, largely as a result of redistribution by waves and burial by fresh sand. The fresh sand coating is very thin, and the conch shells protrude through it in places.

The vegetation has changed considerably; the coconuts have gone, the Avicennia is broken and dead, and only one or two of the Coccoloba, much broken, survive. By contrast, in March and April 1962 the cay surface supported a variegated array of strand plants, many of them not present before the hurricane. Portulaca oleracea is most widespread, in characteristic circular patches, together with the sedge Cyperus planifolius and grasses such as Sporobolus. Small areas are covered with Sesuvium portulacastrum, Euphorbia mesembrianthemifolia and Ipomoea pes-caprae. Other plants represented and collected were Cakile lanceolata, Fimbristylis cymosa, Philoxerus vermicularis and Solanum lycopersicum. Nearly all the Rhizophora seedlings were destroyed, but a number of new ones were growing in the northern depression and near the old house foundations. Two seedlings of Tournefortia gnaphalodes were noted but not collected. There is little chance, however, of a natural succession being observed; a caretaker is to live on the island, and in April 1962 he and I planted over 40 young coconuts on the cay, which should begin to bear by 1970.

There were two casualties during the Hurricane: Jack and Viola Reyes, who lived on the cay when it was the headquarters of the Cambridge Expedition to British Honduras 1959-60, disappeared there during Hurricane Hattie.

Other sand cays of the Northern Barrier Reef

Mention must be made of the former existence of other coral islands on the northern barrier reef:

Curlew Cay is described by Speer (1765, 19) as "very low" with "only a few bushes" and comparable to Paunch Cay. In 1830 it was charted by Owen 1 mile south of Sergeant's Cay and due east of Water Cay. It was again charted by the Rambler in 1896-7, but disappeared some time after that date, possibly in the 1931 hurricane. In 1960 it existed as a small sand-bore 20 yards long and 2 feet high, lacking vegetation; and it is so marked on the 1960 edition of Admiralty chart 522. It was not seen after Hurricane Hattie.

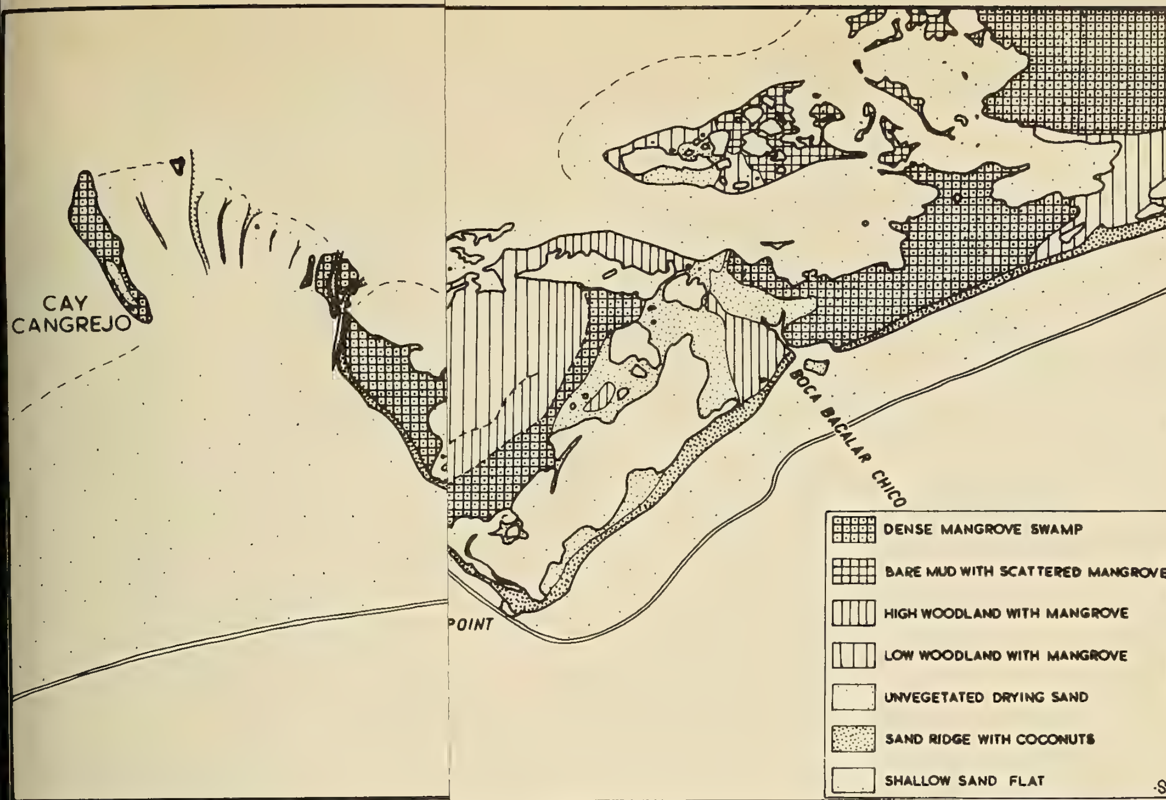
Seal Cay was also noted by Speer (1765, 19) as "a very low, small, sandy Kay, called Seal Kay", located "about 3 quarters of a mile, E.S.E. from Goff's Kay". It was not charted by Owen, but the Rambler survey noted a

sandbore at this point. It was not seen during our own surveys, nor by the 1957-8 Vidal survey.

Sandbore south of English Cay. The Vidal charted a sandbore 650 yards SSW of English Cay. When visited in 1960 this was a strip of sand 60 yards long and 10 yards wide, rising to a maximum height of 3 feet above sea level, and unvegetated. It was not charted by either Speer or Owen; nor was it seen after the hurricane. It was probably never been a true vegetated island, at least in recent centuries.

Samphire Spot is located midway between English and Rendezvous Cays; it was charted as "Saphire Kay" by Jeffreys in 1775 but omitted by him in 1792 and 1800. It was not noted by Speer or Owen, but appears as "Samphire Spot" on charts following the 1896-7 Rambler survey. In 1959-61 it was a small unvegetated sandbore, barely awash, and apparently stabilised by a large stranded log; presumably it disappeared during Hurricane Hattie, but in 1962, though the log had disappeared, the island was larger than formerly, with a diameter of 25 yards, but still unvegetated.

Jack's Cays. This name has been given to sandbores south and east of Rendezvous Cay, one on the end of a linear segment of the barrier reef, one on a patch reef to leeward. Only the former was seen in 1959-60, and then only intermittently, depending on the weather. It was generally 30-40 yards long and 2-3 feet high. The second was seen in 1962, where no sandbore had previously existed; it was 20 yards in diameter, though later it became smaller. At this time the first sandbore was also larger than usual, probably as a result of increased amounts of debris provided by the hurricane.


CAY CANGREJO
POINT
BOCA BACALAR CHICO
DENSE MANGROVE SWAMP
BARE MUD WITH SCATTERED MANGROVE
HIGH WOODLAND WITH MANGROVE
LOW WOODLAND WITH MANGROVE
UNVEGETATED DRYING SAND
SAND RIDGE WITH COCONUTS
SHALLOW SAND FLAT

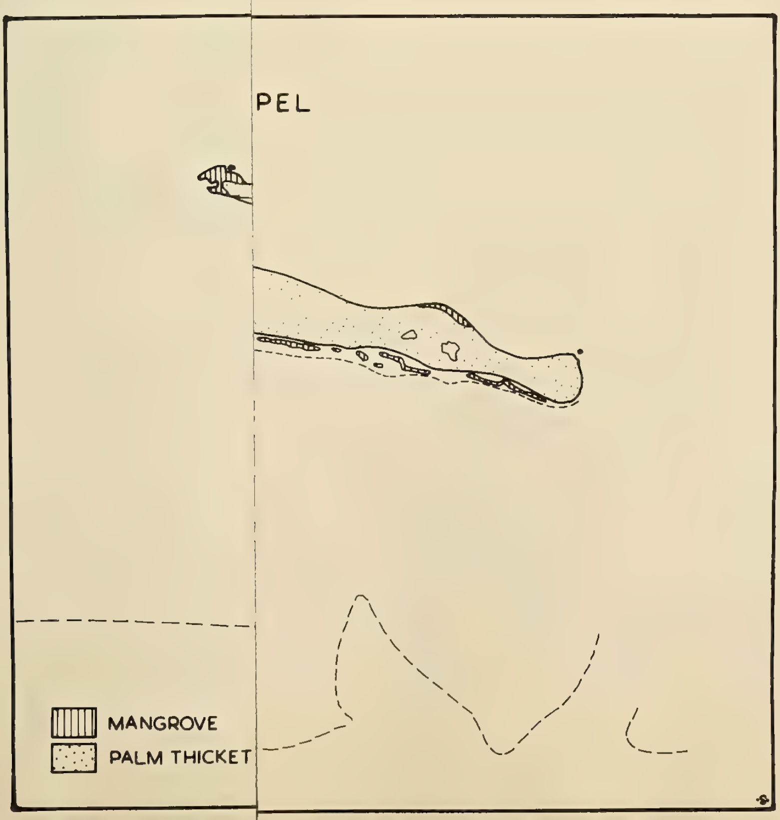

PEL
MANGROVE
PALM THICKET

FIG. 18

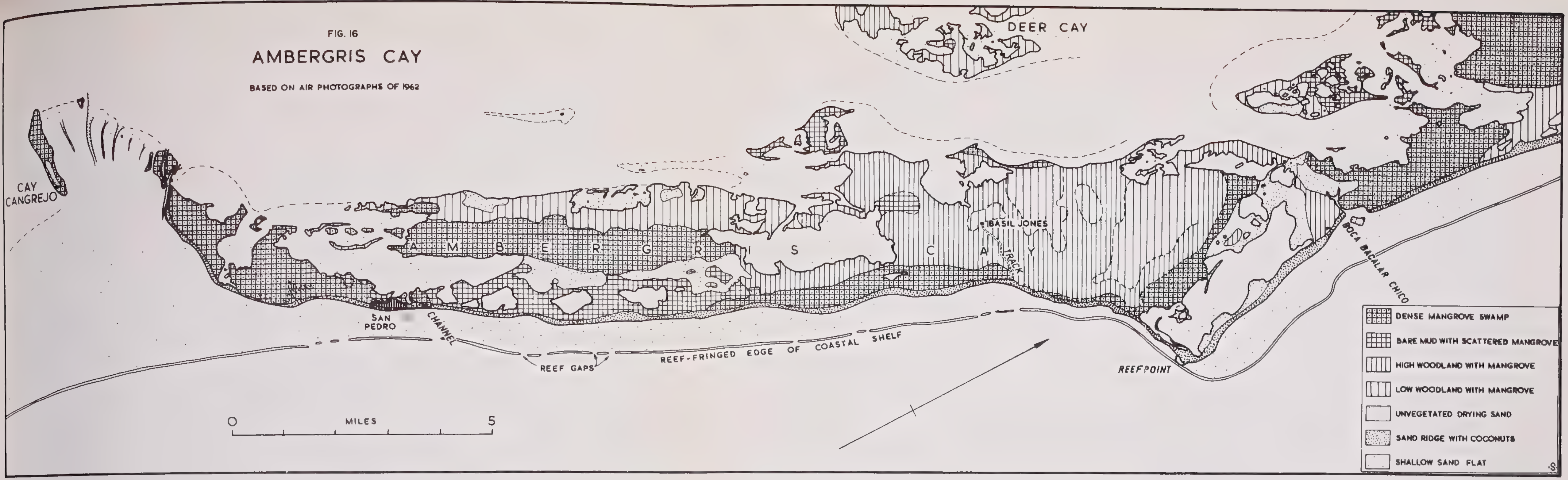


FIG. 16
AMBERGRIS CAY
BASED ON AIR PHOTOGRAPHS OF 1962
DEER CAY
CAY CANGREJO
A M B E R G R I S C A Y
BASIL JONES
TRACK
BOCA BACALAR CHICO
SAN PEDRO
CHANNEL
REEF GAPS
REEF-FRINGED EDGE OF COASTAL SHELF
REEF POINT
O MILES 5
DENSE MANGROVE SWAMP
BARE MUD WITH SCATTERED MANGROVE
HIGH WOODLAND WITH MANGROVE
LOW WOODLAND WITH MANGROVE
UNVEGETATED DRYING SAND
SAND RIDGE WITH COCONUTS
SHALLOW SAND FLAT

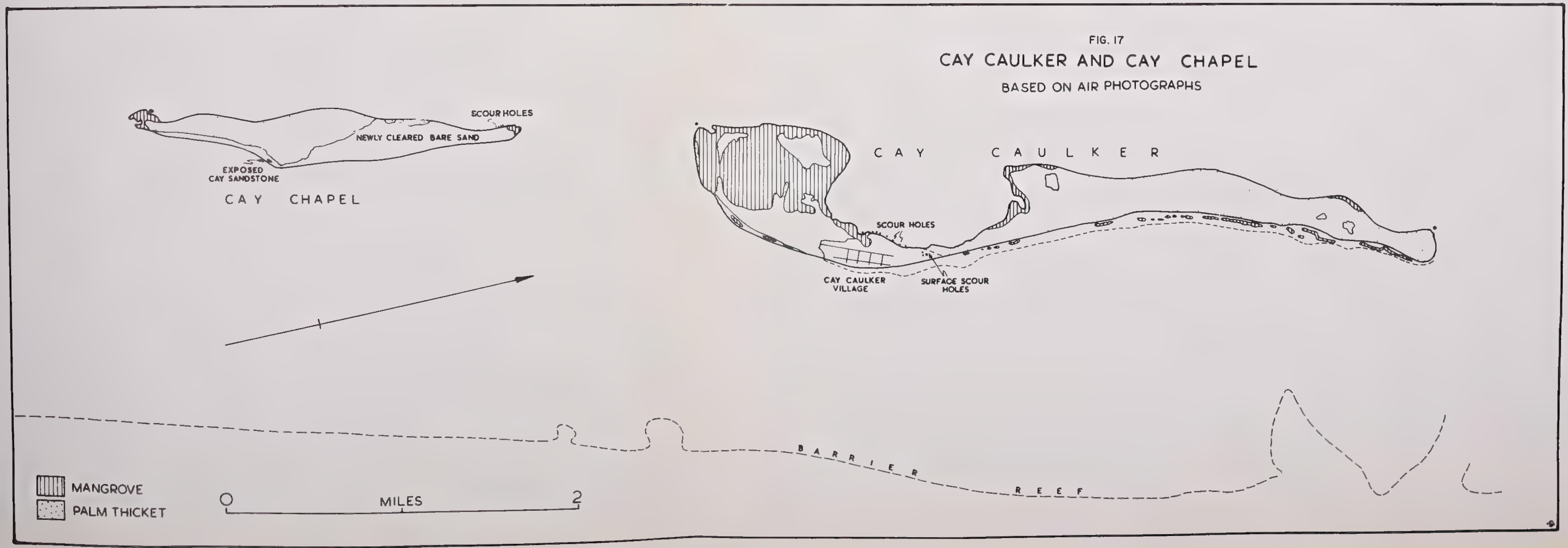


FIG. 17
CAY CAULKER AND CAY CHAPEL
BASED ON AIR PHOTOGRAPHS
SCOUR HOLES
NEWLY CLEARED BARE SAND
EXPOSED CAY SANDSTONE
CAY CHAPEL
C A Y C A U L K E R
SCOUR HOLES
CAY CAULKER VILLAGE
SURFACE SCOUR HOLES
B A R R I E R R E E F
MANGROVE
PALM THICKET
O MILES 2

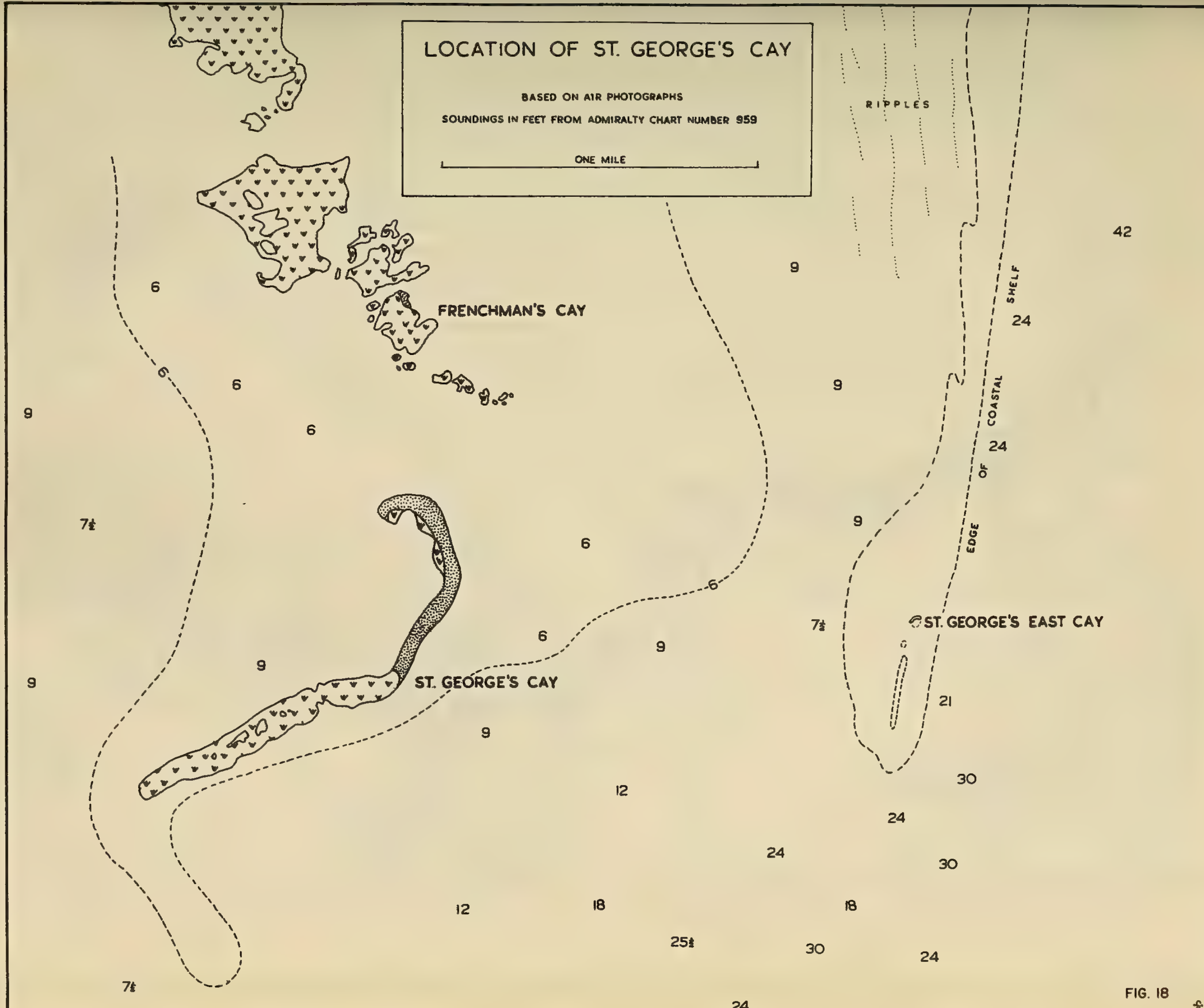
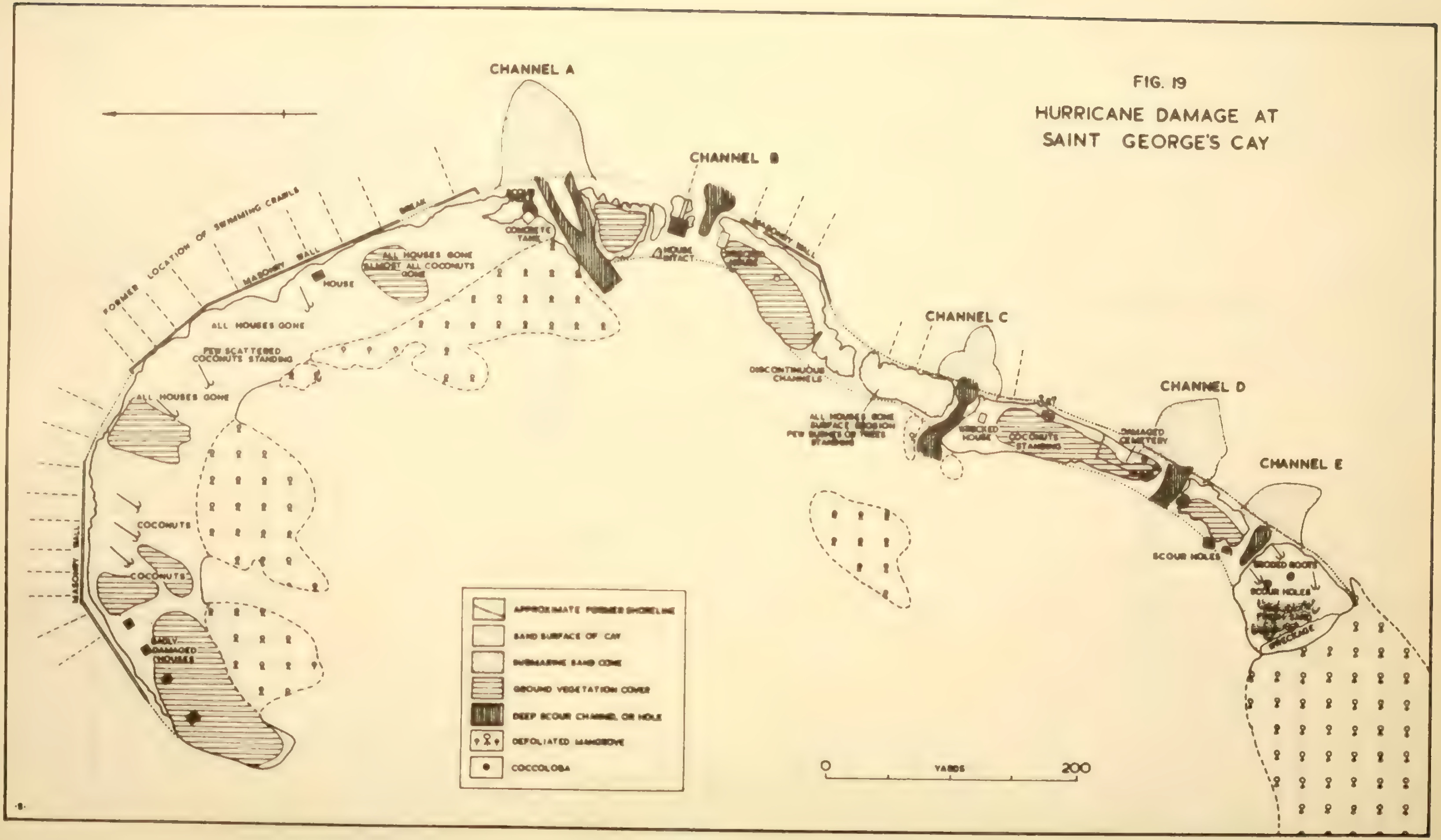

LOCATION OF ST. GEORGE'S CAY
BASED ON AIR PHOTOGRAPHS
SOUNDINGS IN FEET FROM ADMIRALTY CHART NUMBER 959
ONE MILE
RIPPLES
EDGE OF COASTAL SHELF
FRENCHMAN'S CAY
ST. GEORGE'S CAY
ST. GEORGE'S EAST CAY

FIG. 18

FIG. 19

HURRICANE DAMAGE AT SAINT GEORGE'S CAY



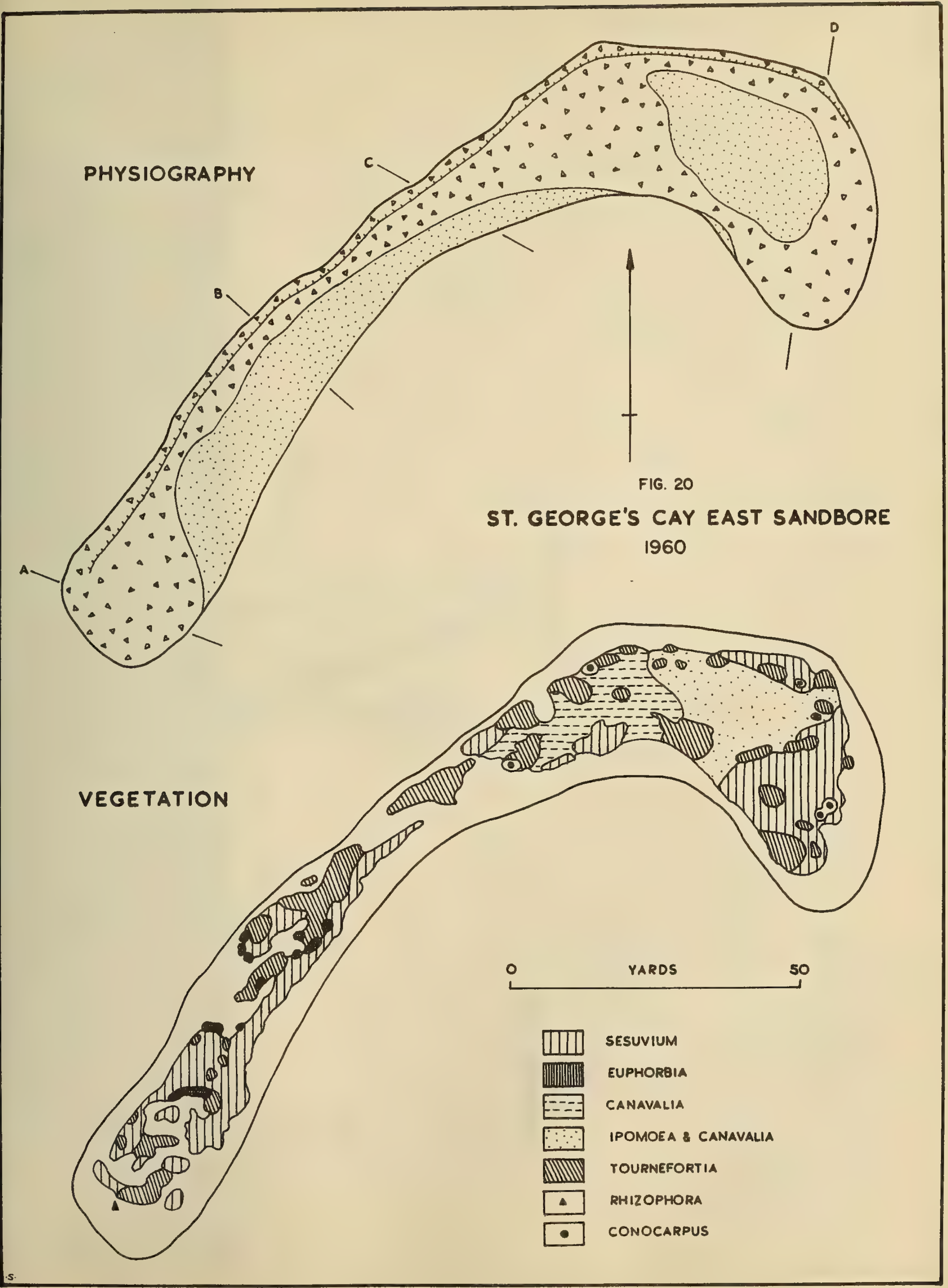
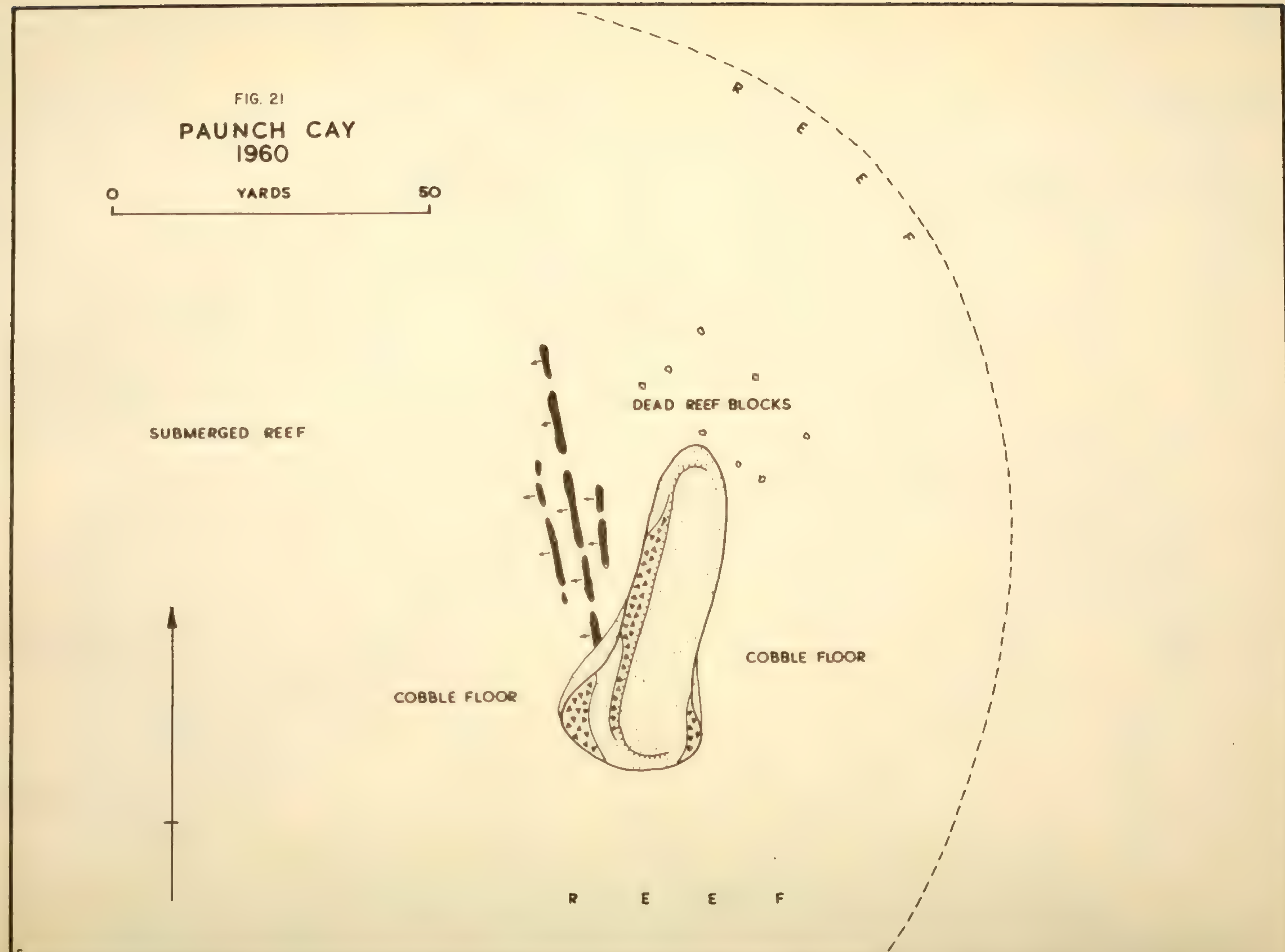


FIG. 20

ST. GEORGE'S CAY EAST SANDBORE
1960

FIG. 21

PAUNCH CAY
1960



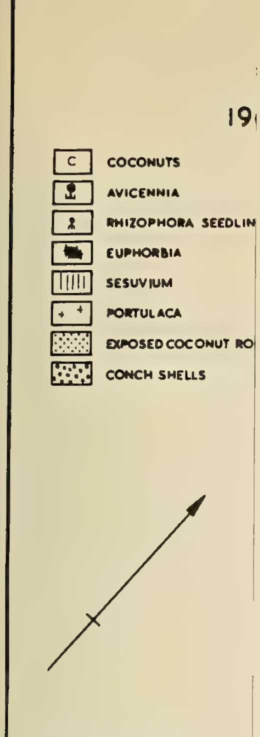
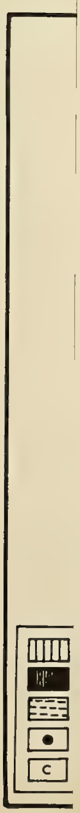

19
COCONUTS
AVICENNIA
RHIZOPHORA SEEDLIN
EUPHORBIA
SESUVIUM
PORTULACA
EXPOSED COCONUT RO
CONCH SHELLS

FIG. 22



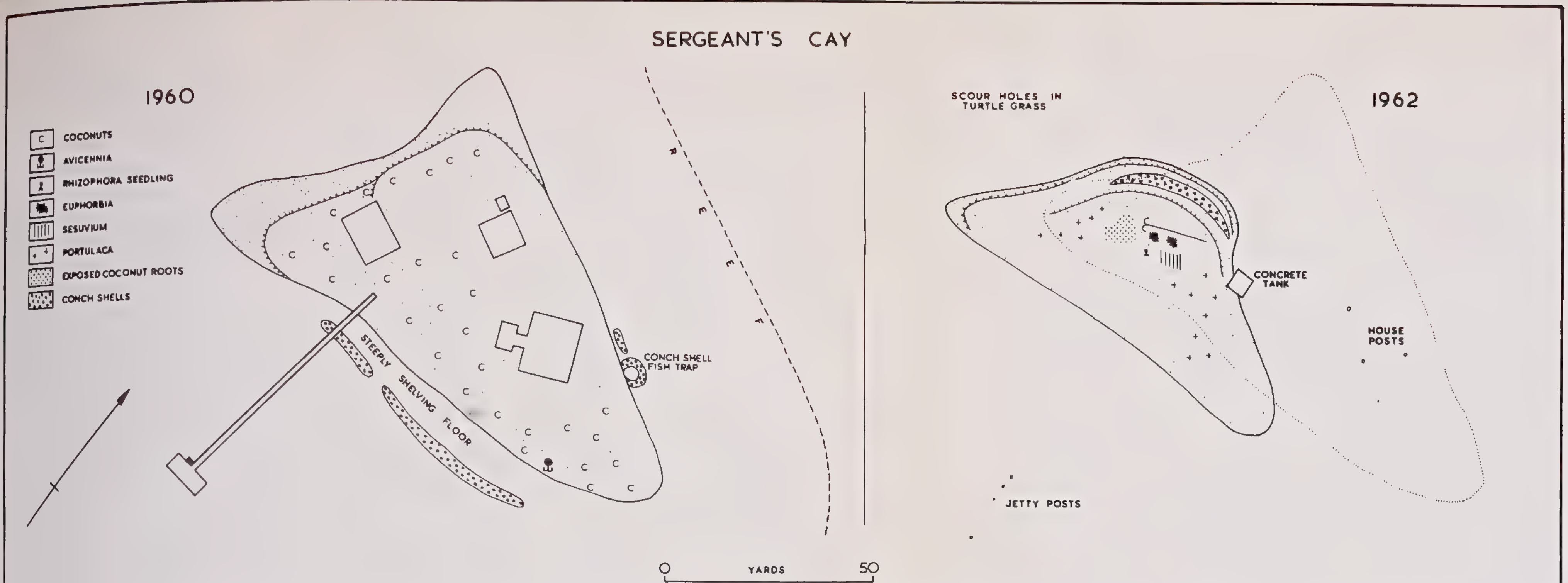

SERGEANT'S CAY
1960
COCONUTS
AVICENNIA
RHIZOPHORA SEEDLING
EUPHORBIA
SESUVIUM
PORTULACA
EXPOSED COCONUT ROOTS
CONCH SHELLS
STEEPLY SHELVING FLOOR
REEF
CONCH SHELL FISH TRAP
1962
SCOUR HOLES IN TURTLE GRASS
CONCRETE TANK
HOUSE POSTS
JETTY POSTS
0 YARDS 50

FIG 22

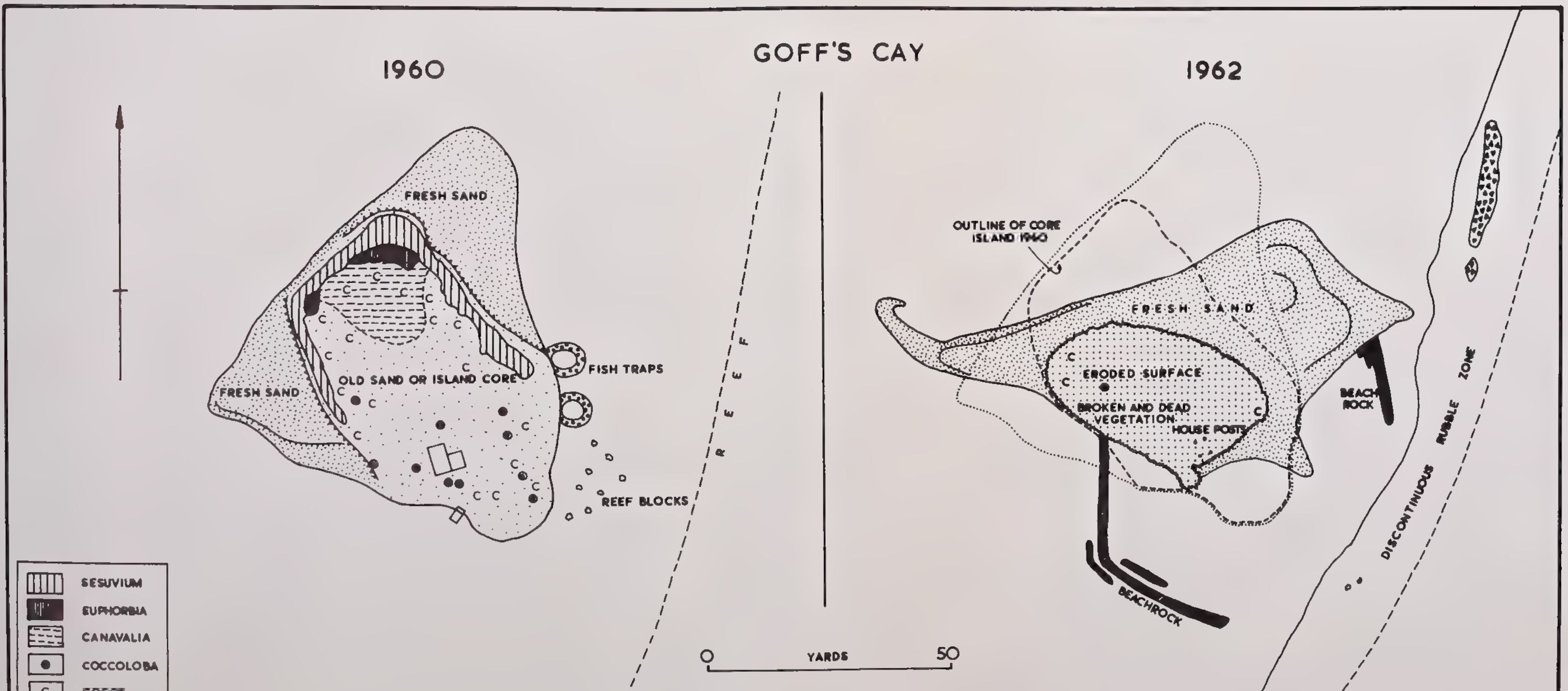
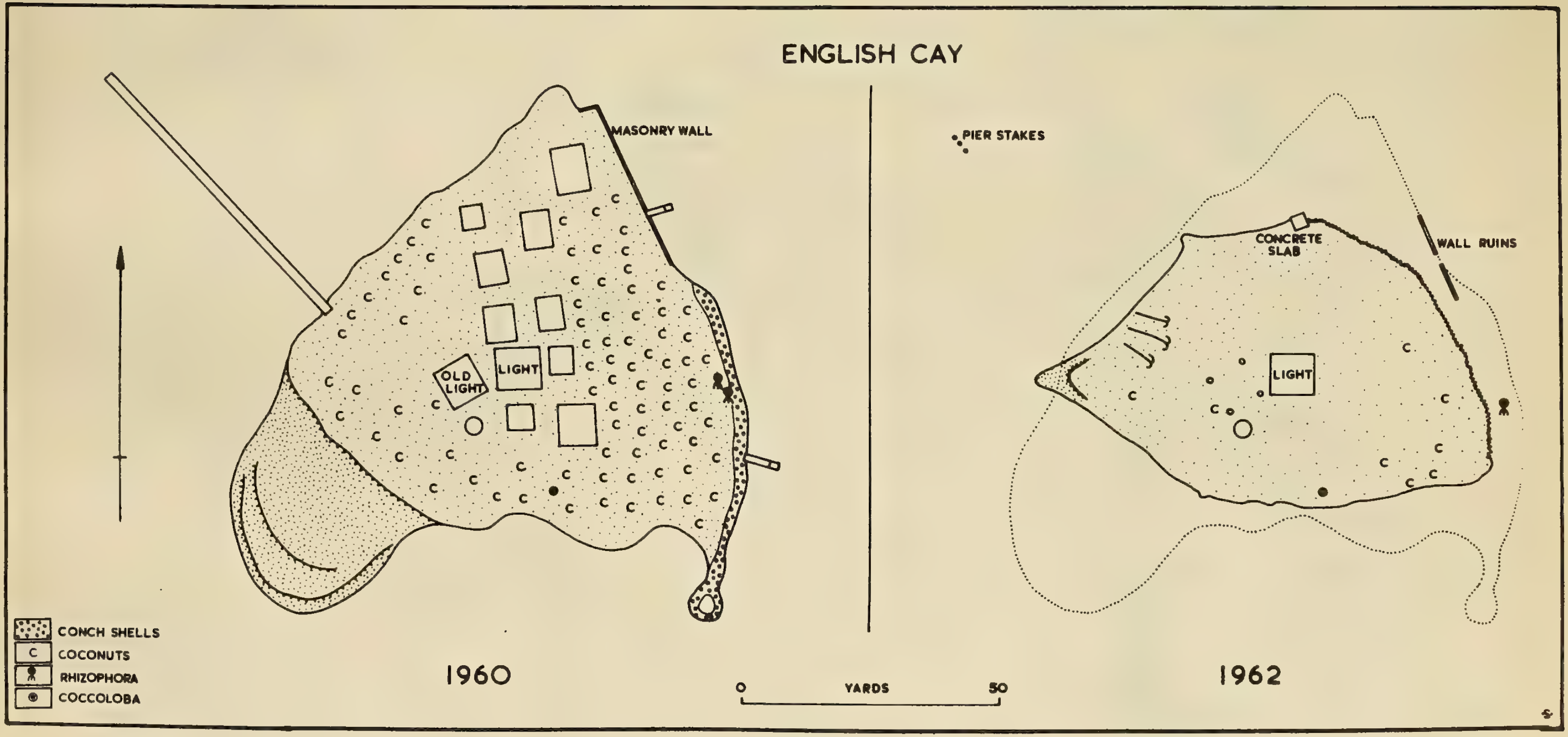

GOFF'S CAY
1960
FRESH SAND
FRESH SAND
OLD SAND OR ISLAND CORE
FISH TRAPS
REEF BLOCKS
REEF
SESUVIUM
EUPHORBIA
CANAVALIA
COCCOLOBA
COCOS
1962
OUTLINE OF CORE ISLAND 1960
FRESH SAND
ERODED SURFACE
BROKEN AND DEAD VEGETATION
HOUSE POSTS
BEACH ROCK
BEACHROCK
DISCONTINUOUS RUBBLE ZONE
0 YARDS 50

FIG. 23



ENGLISH CAY
MASONRY WALL
OLD LIGHT
LIGHT
PIER STAKES
CONCRETE SLAB
WALL RUINS
CONCH SHELLS
C COCONUTS
RHIZOPHORA
COCCOLOBA
1960
1962
0
YARDS
50

FIG. 24

FIG. 25

THE TRIANGLES AND DEEPWATER CHANNEL

BASED ON ADMIRALTY CHART

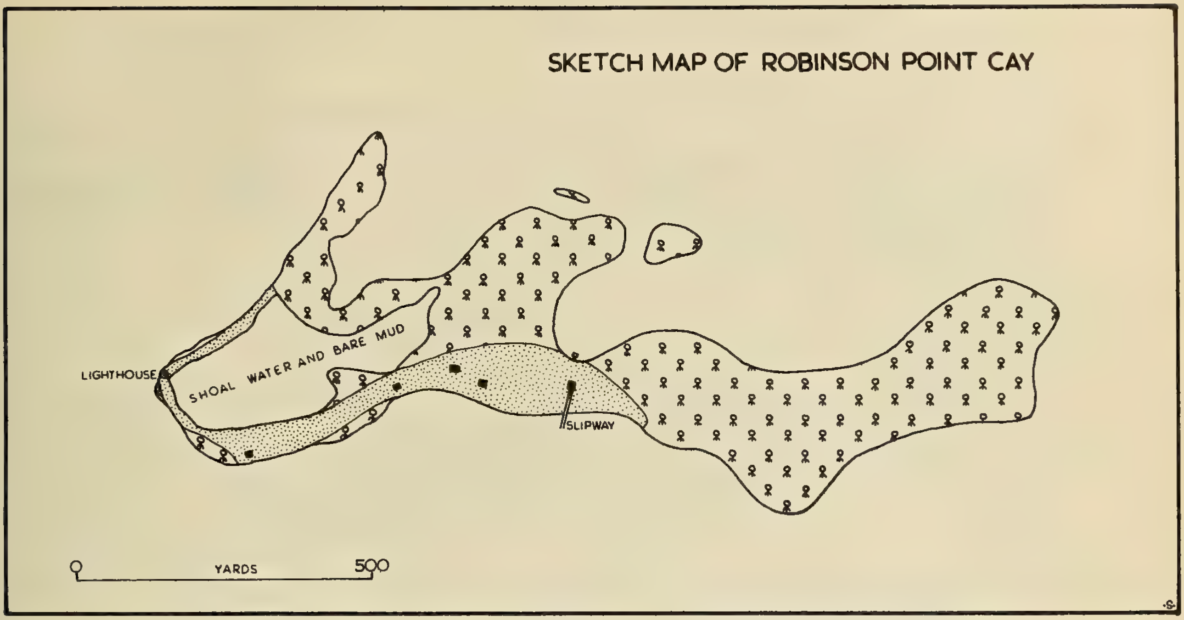

SKETCH MAP OF ROBINSON POINT CAY
LIGHTHOUSE
SHOAL WATER AND BARE MUD
SLIPWAY
0
YARDS
500

FIG. 26

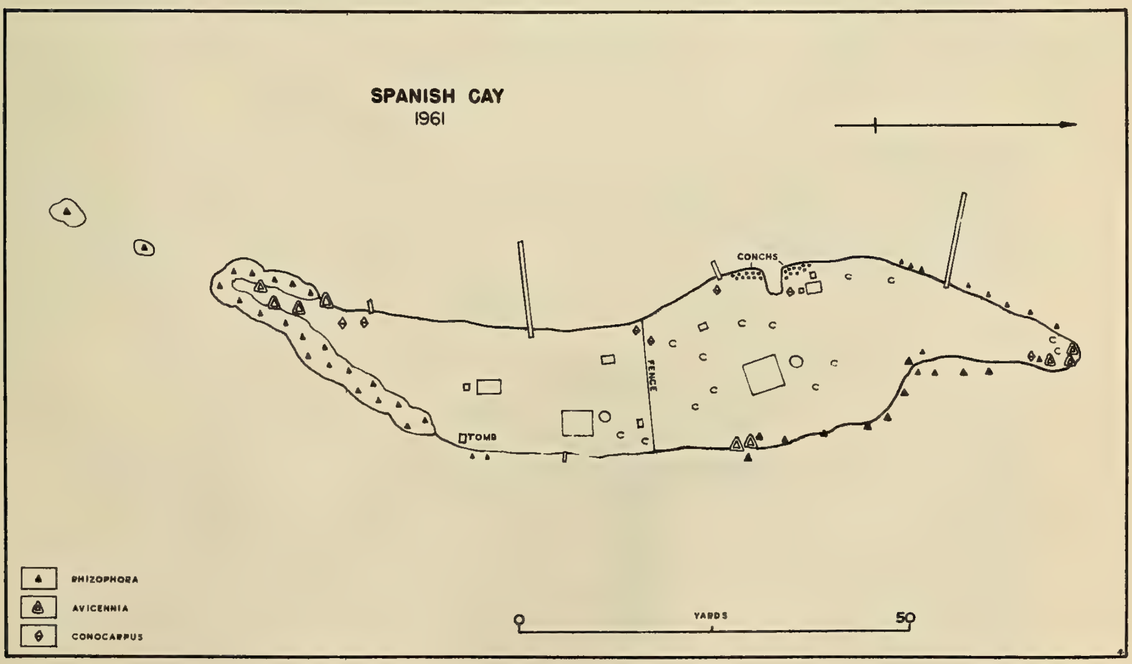

SPANISH CAY
1961
CONCHS
FENCE
TOMB
RHIZOPHORA
AVICENNIA
CONOCARPUS
0
YARDS
50

FIG. 27

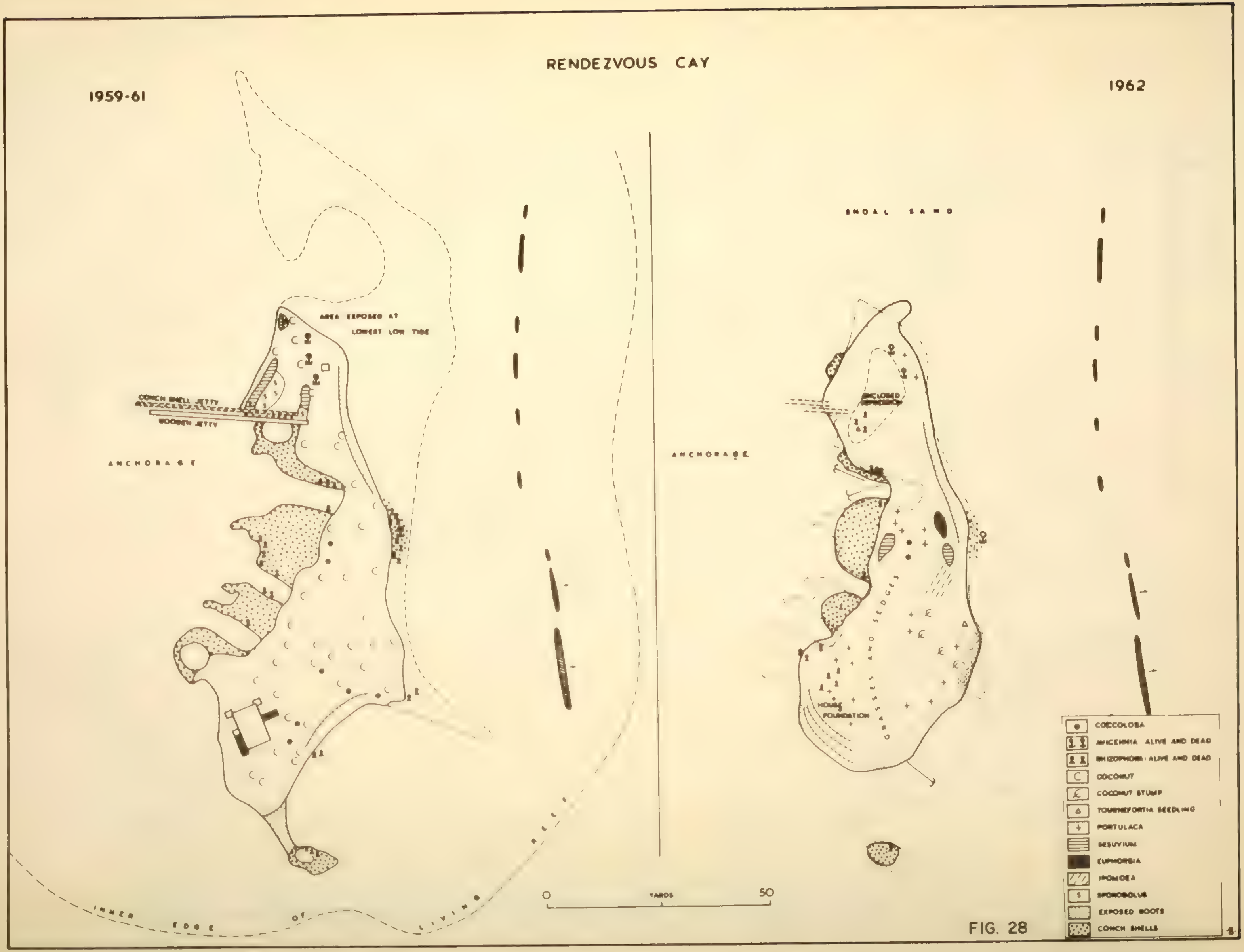

RENDEZVOUS CAY
1959-61
1962
AREA EXPOSED AT
LOWEST LOW TIDE
CONCH SHELL JETTY
WOODEN JETTY
ANCHORAGE
INNER EDGE OF LIVING REEF
SHOAL SAND
ENCLOSED DEPRESSION
GRASSES AND SEDGES
HOUSE FOUNDATION
0
YARDS
50
COCCOLOBA
AVICENNIA ALIVE AND DEAD
RHIZOPHORA: ALIVE AND DEAD
COCONUT
COCONUT STUMP
TOURNEFORTIA SEEDLING
PORTULACA
SESUVIUM
EUPHORBIA
IPOMOEA
SPOROBOLUS
EXPOSED ROOTS
CONCH SHELLS

FIG. 28

V. HURRICANE DAMAGE TO CENTRAL BARRIER REEF CAYS

A. Cays between Rendezvous and Weewee Cays

The barrier reef lagoon between the Deepwater Channel and latitude 16°45'N forms a distinct physiographic region: from the coast the lagoon floor falls steadily eastwards to depths of 10-12 fathoms, the 10-fathom isobath lying an average of 5-7 miles from the coast. At a distance of 7-12 miles from the coast the lagoon floor rises abruptly to a flat shelf-edge platform, 3-5 miles wide and 2-3 fathoms deep, with the barrier reef itself rising to sea level at its outer edge. This wide submerged feature is here termed the "lower platform"; it maintains its horizontality over the whole length of the barrier reef, and is also found on Glover's Reef (ARB 87, 121). Its dissected margins and irregular surface indicate karst erosion conditions during glacial low sea levels, and it is thus at least pre-Würm in age. Two sets of cays are associated with this shelf: the sand cays of the barrier reef, and the mangrove cays rising from the low platform itself. Many of these mangrove cays are linear and elongated north-south, and are situated within a mile of the inner edge of the platform. Examples are Middle Long Cay (Figure 29), Bluefield Range, Alligator Cay and Colson Cays. Others, such as Southern Long Cay, Columbus Cay and Cross Cay, are more irregularly shaped mangrove islands located close to the barrier reef itself south of the Cay Glory elbow. For the most part the barrier reef is remarkably unbroken, and there are few patch reefs rising from the lower platform; exceptions are the numerous patch reefs between Alligator Cay and English Cay, and a group of small patch reefs south of Southern Long Cay. The only extensive area of reef rising from the inner edge of the low platform lies southwest of Fly Range, latitude 16°58½'N.

This section of the coast is well served with charts: Richard Owen made the first outline survey in 1830 and followed this with detailed surveys in the Thunder, 1834 (Admiralty MS H57, L83, L84). The area between Middle Long Cay and Sittee Point was surveyed in very great detail by Capt. H.P. Douglas, HMS Mutine, 1922 (Admiralty MS C8925), and the present charts (959, 1797) are reduced from this survey.

It is not proposed to say much concerning the mangrove cays. Defoliation was intense at Middle Long Cay, and southwards to Colson Cays. At Southern Long Cay, however, latitude 17°05'N, extreme defoliation was apparently limited to northwest and southwest facing shores. *Rhizophora* on these sides was still without leaves in April 1962, whereas trees on the southeast shores were green. This was even more strikingly shown at Cross Cay, 16°59'N; here the south shore of the east-west trending cay is formed by a series of mangrove embayments. In each of these, in April and May 1962, the mangrove on the west side (facing southeast) was green, while that on the east side (facing southwest) was completely bare. It has already been shown in Chapter 2 that south of Rendezvous Cay, where Hurricane Hattie crossed the reef, dominant winds were south and west: the survival of *Rhizophora* at Southern Long Cay and Cross Cay is the first indication of this in the landscape, and corresponds with the exactly reverse situation among the cays to the north of the storm track,

round about latitude 17°33'N (Chapter 4). It is interesting that the lee-side survival of mangrove, or at least its earliest regeneration, takes place about the same distance, 12 miles, to north and south of the storm track, and that within these limits defoliation was total.

For further notes on these mangrove cays and on this section of the lagoon, see Vermeer (1959, 59-71, 79) and Cebulski (1961). The Phillips Petroleum Company is at present (1961-2) drilling a test well west of the northern end of Tobacco Range, which sould provide much information on shelf structure.

Cay Glory

Cay Glory was visited a number of times in 1959 and 1960, and photographed from the air in 1959 and 1961. At this time it was situated on the south side of a reef gap carrying 4-5 fathoms water, some 9 miles south of Rendezvous Cay. It was a narrow strip of sand 115 yards long and nowhere more than 23 yards wide (Figure 30). Winzerling (1946) has suggested that the gap is of largely artificial origin, and was cut to play a part in the outer defences of a somewhat hypothetical Puritan colony at Stann Creek; but this speculation seems to have no factual basis. Northwards the barrier reef extends with few breaks to Rendezvous Cay; southwards it projects to the east in a prominent elbow, backed by a wide, sandy, rippled reef-flat. Two miles south of the cay a number of huts had been erected on the shallow reef-flat, and were occupied during the grouper fishing season; there were two huts there in 1922 and over a dozen in 1960.

The cay was wholly built of sand, with maximum heights of nearly 4 feet along the undercut western shore near its north end. The southern, unvegetated part of the cay was subject to considerable changes: Figure 30 shows its plan in February 1960; when revisited in April the whole west shore had retreated 2-3 feet, the southern spit had decreased in length by 15 yards, and had recurved towards the east. The vegetation cover at the north end was sparse and low, consisting of Sesuvium portulacastrum, Euphorbia mesembrianthemifolia, Philoxerus vermicularis, Cakile lanceolata, Paspalum distichum and Ipomoea asarifolia. There was a single young coconut tree 4 feet high, and the cay was more conspicuous for a small thatched hut than for its vegetation cover.

There is no doubt that the island was formerly more extensive. As late as 1922 Capt. Douglas noted coconut trees 70 feet tall (MS C8925), and many fishermen remember when the cay was larger than at present and was inhabited. It was destroyed in the 1931 or 1945 hurricanes (information differs). Beachrock relics of this older cay are widespread to west and northwest of the 1960 cay, and seem to indicate that the old island was larger than the present. There are four lines of beachrock dipping north, the longest 70 yards long, all massive, slightly undercut, supporting algae and some corals, and little fractured. All these lines were slightly drowned and could be swum over at high tide; modern reef growth extended within the outer lines. More lines of rock dip southwards, one being exceptionally massive, the other being thinner and drowned sufficiently for the growth of Acropora cervicornis colonies on its upper

surface. The massive block was deeply undercut, rose 5 feet from the reef flat and just broke surface. It was the only exposure visible from the island at any stage of the tide. One interesting feature, not marked on the map, was a circle of coral blocks 15 yards in diameter between the two northernmost lines of beachrock, which recalls the conch shell fishtraps built by fishermen on present shores, and may have a similar origin.

During Hurricane Hattie, Cay Glory was completely destroyed, and no cay existed at this point in 1962. The only feature to attract attention was the crest of the massive beachrock still breaking surface. All the beachrock seems to have survived, though completely stripped of corals and algae. The reef flat floor near the beachrock is barren, 5-6 feet deep, and covered with strongly rippled sand. About 20 yards to the east is a steep-sided zone of rippled sand rising to within 2-3 feet of the surface - an embryonic cay which, as at Paunch Cay, will eventually break surface as a sandbore. Round this rippled-sand area the floor is covered with Thalassia, littered with small coral debris; the reef itself (see Chapter 3) has been largely destroyed and replaced by a rubble carpet. The beachrock itself seems more fractured than previously, though this may only be an apparent change resulting from the stripping of algae.

Tobacco Cay

Tobacco Cay (Figure 31) lies at the southern end of a long unbroken section of the barrier reef, 12 nautical miles due south of Cay Glory. The reef flat immediately north of the cay has a width of 500-600 yards; while the lower platform to leeward is here $3\frac{1}{2}$ miles wide and carries $2\frac{1}{2}$-3 fathoms of water, with deeper holes up to $6\frac{1}{2}$ fathoms. Maximum depths in the lagoon here reach 13 fathoms. The Tobacco Cay entrance itself carried 2-3 fathoms, sufficient for small sailing vessels, which even today regularly use this or nearby reef-gaps when making for Glover's Reef. In the eighteenth century the gap was also an important entrance to the barrier reef lagoon: it is marked with great prominence in Speer's 1771 chart, and Jeffreys in 1775 names the cay and also gives soundings in the channel. Caiger (1951, 28-29) follows Winzerling (1946) in speaking of tobacco cultivation here in 1630-1640, but there is no evidence of this apart from the name. The first mention of Tobacco Cay in the colony's archives seems to be in 1753, in connection with alleged English "barbarities" against the Spanish on the cay (Caiger, 1951, 74). The 1922 Mutine survey did not extend as far south as Tobacco Cay, and current charts date from Owen's Thunder survey of 1834. The island was mapped in early 1960, remapped in July 1961 following Hurricane Abby, and mapped again in April 1962 following Hurricane Hattie.

In 1960 Tobacco Cay was roughly triangular, with a greatest N-S length of 300 yards and a maximum width of 150 yards. The whole island was sandy, rising on the seaward side to a height of 5 feet above sea level near the southeast point; but the greater part of the surface was remarkably flat and featureless, with a near constant elevation of $3\frac{1}{2}$-4 feet above the sea. Towards the north and west shores this sinks to less than 3 feet. Conch shells had accumulated along the west shore, and there was a short fresh sandspit at the north point. The largest fresh sand accumu-

lation in 1960, however, was along the south shore, where white sand, contrasting sharply with the dark humic sand of the cay proper, had been thrown up in two ridges, the innermost rising to 3 feet above sea level and enclosing two brackish pools. The shore behind this accumulation, and behind the northern sandspit, was undercut. Two lines of southward dipping beachrock were found 40 yards off the south shore.

The cay was inhabited, with 10 huts, some substantial, in 1960-61, and wells tapping ground water gave a notable supply. In 1960 the island was covered with thick vegetation. In mid-1834 Owen noted trees 70 feet high; Lieut. Smith (1842, 732) stated that "Tobacco Cay cannot well be mistaken, having a high fig-tree (70 feet) near the northeast extreme." In 1960 coconuts were dominant, some reaching heights of 80 feet, together with a number of tall 'almonds', Terminalia catappa, and short bushy Coccoloba uvifera and Cordia sebestena. The undergrowth was dense, mainly of Conocarpus, with a continuous ground cover, consisting of large patches of Stachytarpheta jamaicensis, Wedelia trilobata, Ipomoea pescaprae, I. stolonifera, Sesuvium portulacastrum, Hymenocallis littoralis, with species of Euphorbia, and Canavalia rosea and Vigna luteola. There were a number of Rhizophora seedlings on the west shore. It is worth noting that on the 1945 1:40,000 air photograph cover, vegetation on the cay seemed extremely sparse, probably as a result of the hurricane of the year.

In mid-1961, before Hurricane Hattie, the cay had suffered considerable changes. Hurricane Abby of 15 July, 1960, had swept away the southern sand ridge and the northern sandspit (the new shoreline is shown in Figure 31a), and blown down a number of coconut trees in the south-central part of the cay. In addition, most of the bushes had been cleared by the inhabitants, to give a very different aspect to the island. The ground cover of creepers and recumbent plants, however, remained the same.

The damage caused by Hurricane Hattie may be summarised as follows. The old cay shores were eroded on the east side, and particularly at the southeast point, where the retreat totalled 14 yards. Coconuts roots were exposed by sand stripping along the central part of the east shore, and for short distances near the north point. Fresh sand has been piled up over the old surface along the west and south shores. It is most noticeable along the south shore, where it forms a steep ridge rising to a height of 2-3 feet; and at the southeast point, now rising in a gradual slope to a height of 6 feet, 2 feet higher than formerly. Along the south shore the fresh sand carpet has a maximum width of about 15 yards. About 70% of the coconuts were knocked down, the direction of fall varying from 10-60°, average 40°, indicating winds slightly south of southeast. The greatest sand deposition also indicates similar water movement; but the greatest erosion is on the east, seaward side. In falling, many of the trees left surface holes now filled with brackish water. The island is said not to have been submerged by a storm surge, but the freshwater lens was so contaminated that well water is now almost undrinkable; the inhabitants, who have no alternative, nevertheless survive on it. All the houses collapsed, and in 1962 a single family was living in a makeshift tent of polythene sheeting.

Terminalia resisted destruction in near-shore locations, but *Coccoloba* and *Cordia* were both much broken. Coconuts, including some of the tallest and most fragile-looking, stood on the east and north sides of the cay. None of the fallen trunks have yet been cleared. The cay surface is covered with a very similar plant assemblage to that existing before the storm: *Stachytarpheta*, *Sesuvium*, *Wedelia* and *Ipomoea*; though *Wedelia*, which appears to like shade, was much less widespread, and *Ipomoea* had relatively increased. Much of the *Hymenocallis* was buried by fresh sand but survived. Along the south shore the fresh sand ridge has been invaded and almost completely covered in the period November-April by *Ipomoea*. Other plants collected in 1962 included *Eleusine indica*, *Vigna luteola*, *Eragrostis ciliaris* and *Euphorbia blodgettii*. *Portulaca oleracea*, dominant coloniser on the heavily damaged northern sand cays was seen, but not in profusion.

Cays between Tobacco and South Water Cays

In June 1834 Owen charted three islands along the reef between Tobacco and South Water Cays, with the annotations, "dead trees" ¼ mile north, "trees 15 feet" 1¼ mile north, and "trees 20 feet" 2½ miles north of South Water Cay respectively. The *Mutine* did not find these cays in 1922, nor do they exist today. However, three sandbores were seen here, in these approximate locations, in 1960. Similar sand patches were also seen north of Tobacco Cay. They were all linear, oriented paralled to the reef, up to 50 yards long and less than 10 yards wide, built of very fresh sand, almost overtopped by the waves, and clearly ephemeral. They were not seen in 1961 or 1962.

South Water Cay

South Water Cay (Figure 32) is situated on the northern side of a reef gap, at the end of an unbroken reef segment 5½ miles south of Tobacco Cay. It is prominently marked on Jeffrey's chart (1775), and was last charted by Owen in 1834, when he noted trees 50 feet tall. The general physiography of the reef is similar to that described at Tobacco Cay. The island was mapped in 1960, revisited in 1961, and re-mapped in 1962.

In 1960 the cay had a maximum north-south length of a little more than 700 yards; its width varied from 75 to 200 yards; and it was aligned at an angle to the barrier reef, which it approached closest at its northern end. The island falls into two distinct parts: over the southern three-quarters the natural vegetation has been completely cleared for coconuts, while the northern sector is still partly covered with dense palm thicket. In the centre of the cay there is an area of ornamental gardens with exotic plants, a hard tennis court, tomb (incorporating a freshwater well), and house. At the northeast point, where the shore lies 50-100 yards from the reef, the beach is composed of coral rubble, much pitted and blackened, merging into the scattered debris of the shallow reef flat, and backed landward by a shingle ridge 4 feet high. In pockets in the face of the shingle ridge, small sand beaches have accumulated, composed entirely of *Halimeda* fragments. As the beach trends

away from the barrier reef towards the south the amount of shingle and rubble decreases rapidly, and the greater part of the east shore, before the hurricane, consisted of fine sand, rising to a crest 4-5 feet above sea level, and overlooking a wide, sandy and very shallow reef flat. The reef flat itself is covered with Thalassia: close inshore are numerous Rhizophora seedlings, with a few mature clumps. Behind the shingle ridge at the north end of the cay is an area of black swampy soil with standing water, separated from the lagoon on the northwest side by a low sand ridge, the outer margin of which was slightly cliffed in 1960. In 1960 and 1961 there was a prominent spit of fresh sand at the south point, where the margin of the island core was also undercut, and at the north end of the west bay. No beachrock was seen on the seaward shores of the cay, but immediately south of a 70 yard long masonry wall in the west bay three patches of cemented sand were noted in 1960, emerging from underneath the beachridge. Part of the rock was well cemented, but much was still friable; its outer edge extended 2-3 feet from the base of the beach, and trenching showed that it extended at least 4 feet under the beach sands. Its total thickness was 12 inches.

Almost all the island is covered with coconuts, with a sparse ground cover of Euphorbia blodgettii and grasses; the Mutine survey noted trees 60 feet high in 1921 (West Indies Pilot, I, 463). The northern shingle ridge was covered with a prostrate zone of Sesuvium and a crest-zone of Tournefortia and Suriana. Ground cover in the northern palm thicket consisted of Wedelia, Cakile, Ipomoea, Euphorbia, Cyperus planifolius, Sporobolus and Andropogon glomeratus, with Borrichia arborescens and Coccoloba round the margins. Borrichia and Coccoloba were also scattered along the eastern sand ridge, with patches of Euphorbia and Ambrosia hispida.

During Hurricane Hattie the shoreline retreated discontinuously on all sides of the cay: along the whole of the northwest shore, along the northern section of the west bay (i.e. that part facing southwest), at the south point, and in places along the east shore. Retreat on the northwest shore exposed three patches of cemented sand standing 6 inches above high tide level, with no discernible dip, permeated with coconut roots, and still friable. The exposure lies 120 yards from the north point, where the sand ridge narrows between swamp and sea, and is probably a cay sandstone rather than a beachrock. The incipient beachrock noted in the west bay in 1960 was completely exposed, forming three overlapping lines, now standing 2-3 yards offshore, with a total length of nearly 30 yards. The rock is now generally well cemented, and has a marked lagoonward dip. It is located immediately south of the end of the concrete wall, now much broken and no longer in contact with the shore. The southernmost sand spit was washed away, and the southern part of the cay has the appearance of submergence by the sea. On the east side there are a number of shallow scour holes which may have been cut by southwesterly storm waters crossing the cay surface. Along the shores of the west bay, there is first a narrow beach zone, then an undercut sandcliff, topped by a zone of bare coconut roots from which the loose sand has been stripped, and then a wider but irregular zone of patchy fresh sand, deposited by storm waves. These fresh sand deposits are found only on the west and south shores of the cay.

Tree fall direction is in harmony with the picture of erosion and deposition: direction of fallen coconuts varies from 11-62° and averages 30-40°, corresponding, as at Tobacco Cay, to southwesterly winds. Many trees are still standing at the south and north ends of the cay, but in the centre about 80% of the trees are down. The shores of the northern part of the west bay are lined by the upturned boles of fallen trees. According to inhabitants other trees were defoliated, but in 1962 Borrichia and Coccoloba were still living, and two large Avicennia on the east shore were not killed.

The jetties and some houses were destroyed, but the cay is still occupied and several houses are inhabitable. Most severe property damage was limited to nearshore locations on the west side.

Carrie Bow Cay

Carrie Bow Cay, owned by and named after the Bowman family of Stann Creek, was mapped by Owen as "Jack Ellin's Cay" (H57, 1830) and appears on charts as "Ellen Cay". It is situated at the southern end of a small section of the barrier reef, bounded north and south by channels carrying 1½ fathoms, and it lies about ¾ mile south of South Water Cay. The island itself was an elongate strip of sand 150 yards long and 35-45 yards wide when mapped in 1960 (Figure 33). At the time of this survey a temporary fresh sandspit extended 35 yards to the north of the main body of the cay. The surface of the island is flat, of rather grey sand, rising to a maximum height of 3-4 feet above sea level along the east shore. The eastern beach was then narrow and covered with small loose blocks of dead coral. At the northern and southern ends, where this rocky zone was absent, the shore was slightly cliffed, and littered with fallen and leaning coconut trees. The sand cliff was up to 2 feet high, the top 12 inches forming an impenetrable tangle of coconut roots. The east shore overlooks a shallow and sandy reef flat, thickly covered with Thalassia, with a number of strips of relict beachrock. In 1960 these were not visible from the shore, but were easily seen from the verandah of the house, and from the air. The strips of beachrock were roughly parallel to the beach; Group I (Figure 33) showed no clear dip and were little more than cleared patches in the turtle grass. Between Groups I and II the reef flat was scattered with Porites, Siderastrea, and A. cervicornis, and carried about 2 feet of water at low tide. Beachrock II shows a definite seaward dip; living reef approached within a short distance of this outer exposure. No beachrock was seen along the shores of the cay itself.

In 1830 Captain Owen noted "tops of bushes 20 feet" (Adm. MS H61), probably denoting a thicket of Suriana, Coccoloba, perhaps Cordia, palms and strand plants. By 1960, however, all these had been removed for coconuts and the ground was kept clear of all vegetation, except for scattered grasses and Euphorbia. The island was used as a holiday centre; it had a large house and chalets, and a reinforced concrete pier giving anchorage in 1½ fathoms on the lee side.

Physiographic change during Hurricane Hattie was minor. There was a little shore retreat at the south and north extremities, giving low sand cliffs, and the whole of the east shore retreated 5-6 feet, exposing a fresh line of beachrock (III). This new line of beachrock showed a distinct dip to landward along its whole length (cf. a similar exposure at Southwest Cay II, Glover's Reef: ARB 87, 97). The northern sandspit was also washed away, revealing two lines of poorly cemented beachrock, corresponding to its former shorelines (Group IV). The sandspit in 1960 was low and continually overtopped by waves; it is difficult to reconcile this exposure with the view that beachrock formation is connected with a freshwater horizon (Russell, 1962). A further exposure in Group I was also seen in the Thalassia.

A number of coconut trees still stand, especially at the north end; fallen trees trend from 345-035°, and average almost due north, indicating more southerly winds than at Tobacco and South Water Cays. The jetty was undamaged, while damage to buildings was considerable, though all except one house stood. A boat is now stranded near the north end of the cay, presumably by storm waves. The only plant coloniser since the hurricane appears to be Euphorbia. The island has a resident caretaker. Damage to the reef has already been outlined (Chapter 3); southeast of the cay in April 1962 a strip of coral rubble broke surface to form a ridge everywhere less than 2 feet high.

Curlew Cay

Curlew Cay (Figure 34) must at one time have been very similar in appearance to Carrie Bow Cay, one mile to the north. Here also Owen noted bushes 20 feet high in the 1830's (H61), but in 1960 and 1961 the island was simply a low, crescentic sandbore, 40 yards long and up to 10 yards wide, built of fresh sand and unvegetated apart from two Rhizophora seedlings. Traces of the older island can be seen in the extensive development of beachrock east of the cay. There are three distinct exposures. The first trends SW-NE and shows a characteristic dip to the NW; it was thickly covered with algae, just broke surface, and was partly buried by the sandbore. The second consisted of a single line of beachrock trending E-W; it was rather more submerged and dipped to the north. The third lies 60-70 yards seaward of the first zone, was 1-2 yards wide and its upper surface lies 1-1½ feet below sea level. At its northern end it was a low mound with no discernible dip; in the south the dip was definitely seaward. This line of rock marked the inner edge of living reef, and the rock itself was colonised by Porites and Millepora. The area enclosed by these three zones of beachrock carried 2 feet of water, and its floor was covered with Thalassia and scattered Porites. It is unlikely that the beachrock was all of the same age. The date of destruction of the vegetated cay is unknown; it may have been during the great hurricane of 1945.

Curlew Cay presumably disappeared after Hurricane Hattie, but by April-May 1962, it had again built up, a few yards to the west of its 1960 position. The beachrock was undamaged. The cay is still unvegetated and of fluctuating dimensions.

B. Cays of Central Barrier Reef Lagoon

South of Curlew Cay the barrier reef is fragmented for four miles to South Cut, and thereafter is continuous and without sand cays for the 14 miles to the Gladden Spit elbow. The next southernmost sand cays on the barrier reef proper are 21 miles due south of Curlew Cay. At the Gladden Spit elbow the coastal shelf and lagoon reach their widest extent of 23 miles; in this latitude the maximum lagoon depth is 19 fathoms. Within this area, delimited by Sittee River and Great Monkey Cay on the coast, and by Curlew Cays and Silk Cays on the barrier reef, is an area of extremely intricate bottom topography, with a large number of cays, both sand and mangrove. The bottom topography cannot be discussed in detail, but some brief consideration is necessary for an understanding of the development and location of the cays.

The floor of the lagoon, as in the north, falls away from the coast toward the barrier reef, reaching maximum depths at distances of 10-14 miles from the coast, or generally two-thirds the width of the coastal shelf. Near the edge of the shelf there is an abrupt rise to the lower platform at 2-4 fathoms depth, which is itself edged on the seaward side by the present sea level barrier reef. The greatest depths in the lagoon increase from 12 fathoms in the latitude of Curlew Cay to 24 fathoms in the latitude of Silk Cays, a straight-line distance of 21 miles. This increase in maximum depth is about ten times greater than that between the Triangles and Curlew Cay (2 fathoms in 40 miles), but still gives a north-south gradient of only 1:1800. Figure 35 shows the distribution of depths less than three fathoms in this part of the lagoon; this isobath approximately delimits the lower platform. Note how a long narrow submerged spur trends away from the main lower platform near South Water Cay, and continues southwards by Blue Ground Range to Peter Douglas Cay. From there, Admiralty charts, based on the 1830-34 surveys, show the continuation southwards of arcuate ridges, parallel to the barrier reef and convex to the east. The most prominent of these is that connecting Crawl Cay, Baker's Rendezvous, Cary Cay and Long Cocoa Cay. East and west of this ridge dozens of smaller patches, some with cays, many without, rise to or near the surface. These are apparently concentrated along an axis extending from Placencia on the coast to Gladden spit; in this latitude many of the patches support cays. Immediately to the south of this axis is an area of numerous shoals rising to within 3 fathoms of the surface (Pantile Heads), without cays; and yet further south a zone of apparently similar patches which do not rise above a depth of 4-5 fathoms. Finally, there is a zone where such shoals are almost entirely absent. This depth-distribution may suggest differential movement along an axis transverse to the barrier reef lagoon, which may also have shaped the Gladden Spit elbow. It is clear that the difference in height of the patches is not a reflection of differing degrees of reef growth depending on differences in depth of the lagoon floor; for in this case the tops of the patches would become deeper the farther from the shore, and this is not so. But the problem here is more complex than simple warping or faulting about an east-west axis, for the topographic highs are themselves not simple features. In those close to the shore corals are not significant, and it is probable that in all of them present-day corals only veneer pre-existing structures.

Figure 36 is derived from an airphoto mosaic of the area between South Cut and Mosquito Cay; for its precise location, see Figure 35. The intricate nature of the "patches" is at once apparent: many form elongate, almost closed rings, rising extremely steeply from depths of 15 fathoms or more. The rims of these rings are everywhere narrow, rise to within three fathoms of the surface, and are interrupted by deep gaps; they enclose a central "lagoon" with depths often comparable to those outside the rim. These ring-like features vary up to 7 miles in length, but most are smaller. Cays are located at intervals on the rims. The rims themselves have a further distinguishing characteristic: their outer margins are smooth in plan and gently curved; the channels between the rings pass smoothly into each other without marked angles; and their general shape is smoothly curvilinear, or lozenge-shaped. But the inner edges of the rims are intricately dissected and highly irregular. The upper surface of each rim is also irregular and pitted with deep holes. The only extensive surface-breaking reef is that between Baker's Rendezvous and Crawl Cay, but most of the patches have moderate reef growth on their eastern sides.

These features are clearly not the result of modern reef growth; their general form and intricate dissection point to karst erosion during glacial low sea levels. The channels between the patches may represent lagoon floor drainage channels of glacial age. It is possible that part at least of their form results from solution weathering of limestone of the type described from Okinawa by MacNeil (1954) and demonstrated experimentally by Hoffmeister and Ladd (1945); some of the small patches, with their arcuate outline and deep holes, recall in a striking way the small elevated limestone islands of the Palau Archipelago (Fosberg, 1960, Plate 12), except, of course, that in British Honduras the forms are entirely submarine. They may originally have been extensions of the Tertiary limestone hills of the mainland, or old reef forms, but in the latter case it is difficult to explain their absence in other parts of the barrier reef lagoon. Very similar features lying at greater depths (4-7 fathoms) can be traced on air photographs at the southern end of the barrier reef, west and southwest of Seal Cays. These may represent erosion features either down-warped since foundation or developed at a lower level on lower limestone masses. If down-warping or faulting has occurred it must have predated the foundation of the horizontal lower platform. The idea that the patches have developed on drowned limestone hills explains more easily their restricted location and entire absence over the greater part of the lagoon. If the features did predate the lower platform they were presumably all truncated at the 2-4 fathom level when the platform was formed. Enough has been said to indicate that the recent history of this part of the shelf may be more complex than Vermeer (1959) supposed; deep drilling for oil at Placencia may help unravel events when the results are available.

In the following sections the cays of this central barrier reef lagoon are discussed in turn from north to south. No early descriptions of these cays exist: it is not possible to identify Speer's (1765) brief references, nor to reconcile the rather schematic charts by Speer (1765, 1771) and Jeffreys (1775) with modern maps. Only the present False Cay and Placencia Cay were named by them; the rest were grouped as Reed's Cays (Tobacco and Blue Ground Ranges?) and the Coconut Cays (all the rest). Jeffreys (1775) additionally names Bugle, Colson, Scipio and adjacent cays the "Placentia Triangles".

Weewee Cay to Baker's Rendezvous

Weewee Cay lies on a reef patch 4 miles west of the barrier reef and $4\frac{1}{2}$ miles southwest of South Water Cay. It is a small triangular island with sides 100-150 yards long, enclosed on the north and southeast sides by dense mangrove. Rhizophora also extends along the greater part of the N-S trending west shore, except for a small opening giving access to the low-lying sandy interior. In April 1962 the peripheral mangrove was still alive along the north and southeast facing shores, and had been killed only at the southern tip, where for a short distance the shore trends N60°E. Living reef fringes the entire eastern side of the cay, but is absent along the west side; a protected situation presumably accounts for the absence of a weatherside sand ridge on the island, and the apparent reversal of physiographic zones compared with the normal mangrove-sand cay. The cay is not permanently inhabited, but is used as a fishing station by Stann Creek Caribs; a number are buried on the island under piles of conch shells. Fish are cleaned, salted and dried (corned) here. The dry land area has a circumference of about 75 yards; its vegetation is restricted to coconuts and an undercover of grasses and sedges including Cyperus peruvianus, Fimbristylis cymosa, Chloris petraea and Batis maritima. A large number of trees was knocked down by Hurricane Hattie; direction of fall varied from due north to due south, with a few due east and due west. The pattern is in fact almost radial, perhaps as a result of the enclosed character of the dryland area; perhaps 50% of the measured directions lay between 345° and 045°, indicating predominantly southerly winds.

Stewart Cay (un-named on charts, bearing 316-323° from Weewee Cay) and Bread-and-Butter Cay (bearing 274-282° from Weewee Cay, named Stewart Cay on charts) are mangrove islands, lacking dry land, with no important hurricane effects except mangrove defoliation on south-facing shores. Crow's Nest Cay (Spruce Cay on charts) lies $2\frac{1}{2}$ miles SSW of Weewee Cay; it is entirely of mangrove, and because of its sheltered position escaped much defoliation. Peter Douglas Cay (Douglas Cay of charts) lies $1\frac{1}{2}$ miles SW of Crow's Nest Cay; the intervening Norval Cay of charts was not seen in 1962. Peter Douglas is a large island, mainly mangrove, of irregular outline, fringed by reef on its northeast and east sides. Rhizophora on the northeast and southeast shores was not seriously defoliated; but complete defoliation occurred at the south point, and along the west shore a number of tall Rhizophora had been uprooted, apparently by south-westerly waves. There is a small area of dry land on the west side of the cay; nearshore, it is formed of coarse sand with much shell debris, rising $1\frac{1}{2}$ feet above the sea; it extends for an unknown distance toward the centre of the cay, and supports a dense palm thicket with Sophora tomentosa. According to informants there were about 30 coconuts before the hurricane; 12 were counted afterwards. Little Peter Cay is a small island immediately to the south, the greater part being defoliated Rhizophora, with Sophora on the dry land area; and immediately to the south of this lies another very small mangrove island, Old Rendezvous Cay, almost completely defoliated. Neither of these small islands is named on charts.

South of Peter Douglas Cay, Saddle Cays (Elbow Cays of charts) were not visited, but instead we sailed through Northeast Cay Range, the Pelican Cays of charts, in latitude 16°41'N. These cays are situated midway between coast and barrier reef, here 7 miles distant. They consist of a single large mangrove cay, Northeast Cay, with many small mangrove cays, defoliated on the west side, some with small amounts of shingle thrown up on the west shore. Of these, Cat Cay lies on the southwest side of the group. It is a small island with a narrow fringe of Rhizophora on its north and east shores, and along the greater part of the west shore also. The greater part of the cay is dry land, though the centre is low-lying and marshy, with scattered Avicennia. Fresh small shingle has been thrown up along the west shore, and a number of coconuts have been knocked down. Direction of fall varies from 270-020°, with the majority 340-360°, again indicating southerly winds. The vegetation of the dry land area includes, in addition to coconuts, the palmetto Thrinax, and Thespesia populnea; together with Conocarpus erectus, Euphorbia sp., Cyperus sp., Wedelia trilobata, and grasses. Ospreys (Pandion halietus) were nesting here in 1962. Man-of-War Cay is one of the southernmost of the Northeast Cay Range. In April-May 1962, though small and consisting only of almost completely defoliated Rhizophora, it was inhabited by large numbers of Fregata magnificens, preparatory to nesting. This bird was not seen on any of the neighbouring cays at this time.

Other cays merit little comment. The two Lagoon Cays so called because they each enclose deep lagoons (the larger carrying 8 fathoms), and Crawl Cay are entirely mangrove; Quamino Cay is almost entirely mangrove, with a little dry land on its east side. Glasher Sand Bore, where Owen noted trees 15 feet high in 1830, has not been visible for many years, but reappeared as an unvegetated sandspit following the hurricane. Baker's Rendezvous consists of two long mangrove islands and two much smaller ones to the south; they are wholly mangrove, except for two coconuts on the southern long island. All these cays show some mangrove defoliation on their south shores.

Cary Cay

Cary Cay (Figure 37) occupies a very similar position to Crawl Cay and Baker's Rendezvous, but is much further south, where the linear reef on which it stands trends NNE-SSW, rising from maximum depths of 17-18 fathoms. The island itself trends north-south, and has a maximum length of 500 yards; its width varies, from a narrow sandy strip only 10 yards wide in the south, to a 200 yard wide mass of Rhizophora in the north. Reef extends along the whole east side, but not on the west. Along the east side of the island there is a narrow dry-land area, with palms and strand vegetation; and a lower dry area, planted to coconuts, extends along much of the west side. These two dryland areas diverge northwards, and the intervening area is occupied by standing water, Acrostichum marsh, and, towards the north Rhizophora.

During the hurricane, fresh shingle was thrown up for 400 yards along the east shore, and also in the form of separate ridges at the south end. These shingle spreads consist mainly of cervicornis debris; the separate

ridges have a maximum height of 2-2½ feet, though on the southern tip of the cay the shingle is piled against vegetation to a maximum height of 5½ feet. In places along the shore there are small stretches of erosion, with cliffing and root exposure. Immediately offshore, toward the south, are numerous scattered coral blocks, mostly less than 1 foot diameter. The main western shingle ridge varies in height from 2-5 feet, and in width from 10-20 yards; it is often higher where narrower, because of banking against vegetation. The inner edge of the shingle ridge, where it abuts against standing water rather than vegetation, is characteristically steep. The calibre of the material varies from fine shingle up to coarse rubble and some large coral blocks.

Near the north point, and along much of the west shore, the sandy beach is slightly cliffed, in spite of patches of protecting Rhizophora. Thin blankets of fresh sand cover the nearshore area in the south. The vegetation of the dryland area consists of coconuts, Thrinax (especially along the northeast shore), Coccoloba, Cordia sebestena, and an undercover of Hymenocallis, Wedelia, Ageratum, Stachytarpheta, grasses and sedges. Only a few coconuts have been knocked down, and these have generally fallen to the north and northeast. The Acrostichum aureum marsh is surrounded by Avicennia and Rhizophora. Major hurricane effects at Cary Cay are thus practically limited to shingle and sand deposition, apparently in response to mainly southeasterly waves.

Trapp's Cay

Trapp's Cay (Figure 38), the Moho Cay of charts, lies 2 miles southeast of Cary Cay on an isolated reef patch rising from 18 fathoms. The island is regularly shaped, with maximum dimensions of 260 and 210 yards, N-S and E-W, and an area of some 55,000 sq. yards. The margins of the cay are low and sandy, except on the southwest, south and east sides, where the old shore was buried by fresh shingle during Hurricane Hattie. Underneath this shingle accumulation, and intermittently exposed, the old shore is undercut and eroded; much of the finer material has been washed out, leaving only a root mat. Before the hurricane these shores were probably comparable to the present north and east shores. Vegetation approaches close the shore on all sides, except at the northeast corner, where a new spit of fresh sand is building outwards.

The whole of the east shore is blanketed by a carpet of shingle, varying in width from 10-25 yards, and in calibre from small cervicornis debris to occasional large blocks, including one Montastrea annularis block 3½ feet long. The old shoreline along this side of the cay has clearly been much eroded; its edge can be traced along the centre of the shingle carpet. The old nearshore vegetation has been largely destroyed or buried by the shingle, but in many places broken palmettoes (Thrinax) protrude through the shingle carpet. The inner edge of the fresh shingle is everywhere arcuate in plan and steep in section, rising 18-24 inches above the old cay floor, here low-lying, with coconuts or Conocarpus bushes. Along the south shore the shingle carpet has a similar width but is much thinner, and the eroded old shoreline is visible everywhere within a few feet of the present shingle shore. Patches of a rather soft sand-shingle conglomerate are exposed at sea level at

one point. The height of the step at the landward edge of the shingle is here generally less than 1 foot. Northwards along the west shore, the shingle tails off rapidly in both width and thickness. At is greatest accumulation on the east shore the shingle carpet is probably not thicker than 2½ feet. A low arcuate spread of shingle has been thrown up off the south shore; it is about 100 yards long, and probably did not exist before the hurricane.

The vegetation of the island was not investigated in detail; hurricane effects were limited to near-shore felling of coconuts, largely by wave-sapping of the substrate itself. A large *Coccoloba* was also uprooted on the west shore. Dominant direction of tree fall indicates winds from the south and southwest, in contrast to the southeasterly direction indicated by shingle deposition. *Thrinax* is widespread round the cay margins, and appears to have resisted the hurricane better than coconuts. Other trees noted include *Thespesia populnea* and *Coccoloba uvifera*; with a ground vegetation of *Hymenocallis littoralis*, *Cyperus*, *Phyllanthus amarus*, *Chloris petraea* and *Paspalum paniculatum*. The centre of the cay was not investigated. There are a few *Rhizophora* bushes round the shore.

The name Trapp's Cay is preferred to that given on charts, which invites confusion with other Echo Cays (latitude 17°31½'N, 88°12'W; and 16°09'N, 88°40'W) and is not known locally. Co-ordinates of Trapp's Cay are 16°30½'N, 88°10'W.

Islands between Trapp's Cay and Gladden Spit

Some of the islands lying to the northeast of Trapp's Cay were also visited. *Rendezvous Cay* is a mangrove island with a small central sand area covered with coconuts, used by Carib fishermen but not permanently inhabited. A number of coconuts had been knocked down, their direction varying from 305-355°, with a few 140-150°. As on other cays near Gladden Spit, some of these trees were certainly knocked down by Hurricane Anna in 1961; and there was no doubt that at least two different sets of fallen trees were represented here, distinguished, for example, by greater amounts of fungal growths on the older trunks. *Long Coco Cay* is very similar to Rendezvous Cay, but there has been little damage to coconuts. There is some defoliated mangrove at its southeast point, but no deposits of fresh sand or shingle. This cay was briefly described by Vermeer (1959, 91-92). *Tarpum* and *Jack's Cays* are wholly mangrove, with little of interest. *Little Water Cays*, noted by Vermeer (1959, 91) was not visited, but seemed from a distance to be similar to Rendezvous and Long Coco Cays.

Buttonwood Cay (Figure 39) was mapped in 1960, shortly before its vegetation was severely damaged in Hurricane Anna. The sand area is low-lying, measures 80x100 yards, and is surrounded on its west and southwest sides by mangrove. The vegetation consists of coconuts, *Coccoloba*, *Conocarpus*, *Rhizophora* and *Avicennia*, with *Cyperus planifolius*, *Eragrostis domingensis*, *Portulaca oleracea*, *Euphorbia* sp., and *Vigna luteola*. The name itself is the local term for the buttonwood mangrove, *Conocarpus erectus*. Because of the occurrence of two hurricanes since the island was mapped, it was not thought worthwhile to re-map the cay.

Laughing Bird Cay

Laughing Bird Cay (Figure 40) is the southernmost of the central barrier reef lagoon cays, and the most attractive; it lies $4\frac{1}{2}$ miles from the barrier reef and 6 miles from the coast, on a narrow reef patch, aligned NE-SW. The bottom to the northwest is fairly shallow, but depths of up to 24 fathoms are found within very short distances to the southeast. The island, like the reef on which it stands, is long and narrow, with a total length of nearly 500 yards, but varying in width from only 10 to 45 yards. Before the hurricane the island seems to have been completely sandy, with a beachridge rising to a height of 3-4 feet on the southeast side. The vegetation, which consisted chiefly of coconuts, was distributed in three distinct clumps, the longest in the centre, and the trees were only about 40 feet high. During the hurricane, few of these trees were knocked down, except along the central part of the southeast shore, where the beach itself was cut back and a number of undermined trees fell towards the north. A number of Rhizophora trees on the southeast side were also defoliated and killed.

The dominant storm effect, however, was the deposition of shingle and rubble on the southeast side. These deposits are most extensive towards the ends of the cay, where they blanket the old surface and are piled up against the now dead vegetation; between these extremities there are occasional high patches of gravel, reaching 4-5 feet above sea level, but most of the shingle takes the form of an off-shore ridge 5-10 yards from the southeast beach. The greatest height reached by the shingle on the cay surface is at the bushy northern end, where it is banked up to 6 feet above sea level. At the south end the rubble and shingle forms an arcuate ridge enclosing two stagnant pools of water. It is, of course, impossible to say whether this off-shore ridge was previously more extensive and has been partially eroded since the hurricane, or indeed whether the hurricane succeeded in breaching the sandy island between the vegetation 'islands', though no sign of such breaching was apparent. However, the shingle itself is clearly of hurricane origin, and my local companions, who had previously often slept here, confirmed the changes. The leeward beach is wide, long and sandy, and except at the extremities shows no unusual features. It overlooks a shallow sand-floored anchorage.

The ground cover under the coconuts consists of Sesuvium, Ipomoea, Euphorbia, and in places Hymenocallis. Except where buried by rubble the vegetation seems to have been little affected, except for the mangrove on the windward side.

Owen Cay

Finally, we come to the cays between Laughing Bird and the coast, Jeffrey's "Placentia Triangles". These fall into three groups: (a) those with considerable dry land, on the south and east of the group, including Owen, Scipio and Colson Cays; (b) the mangrove islands, with no dry land, including Lark Cay, once known collectively as "Scruffer's Range" (Owen, 1830) and situated on the north side of the group; and (c) Bugle Cay, a mangrove cay with a narrow sand zone. All these islands are situated on small discrete shoal patches, generally with reef growth, rising steeply from 10-15 fathoms water.

Owen Cay (Figure 41), the easternmost and situated on the most extensive shoal patch lies 2½ miles due west of Mosquito Cay and 8 miles from the coast. It is uninhabited, not named on charts, nor have I been able to discover a local name for it, even from the keepers of the Bugle Cay lighthouse. For ease of reference it is here named Owen Cay, after Captain Richard Owen, first surveyor of these reefs; its co-ordinates are 16°29¼'N, 88°15½'W.

The island is 180 yards long, with a maximum width towards the north end of 40 yards. The centre of the cay is low and sandy, with numerous large _Avicennia_ and _Rhizophora_ trees, and considerable area of _Batis maritima_ (typical of such mangrove-sand cays), _Hymenocallis_, and grasses. There are numerous low coconuts, some _Thrinax_, and occasional _Cordia sebestena_. None of the trees were blown down or uprooted by the hurricane, but shoreline _Rhizophora_ has been defoliated on the south and west sides of the cay, but not on the north and east. The main hurricane effect has been the deposition of peripheral shingle ridges, highest at the southern end, where the shingle is banked against the coconuts, covers the whole surface, and rises to 5 feet above sea level. Elsewhere the shingle carpet is thinner and does not exceed 10 yards in width; it is highest on the west side. Along the east side, where there is some undercutting of the old shore, the shingle has spread out in a wider offshore carpet, 1-2 feet above sea level. The calibre of the shingle is small to medium and the constituents only exceed 6 inches in diameter along the southernmost ridges.

Scipio Cay

Scipio Cay (Figure 42) has much in common with Owen Cay 2¼ miles to the ENE. It is located at the northern end of a small shoal area, surrounded by water 12-15 fathoms deep. The island itself is aligned north-south, is 270 yards long and up to 100 yards wide. The island before the hurricane was largely low-lying, sandy, covered with coconuts, and with a large central _Avicennia_ marsh. Peripheral beach ridges, especially on the east and southwest sides, were thickly covered with _Thrinax_. The rest of the vegetation was limited to scattered _Cordia_, sedges and grasses. Vegetation approached close to the shore and was very dense. When mapped in April 1962 there was considerable undercutting of the old shore along the east and south sides of the cay, exposing mats of characteristic brown coconut and orange palmetto roots. The upper edge of this undercut shore lies 1-2 feet above sea level; landward the cay surface falls rapidly toward the _Avicennia_ marsh or other low-lying ground. It is covered by a wedge of fresh shingle, tapering at the top of the shoreline cliff, thickening landward, where it ends abruptly in a steep slope 1-2 feet high. _Thrinax_ trees protrude through this fresh covering, which is everywhere less than 20 yards wide. On the east side the deposit consists only of _cervicornis_ and small _palmata_ shingle; on the west side the material is sandy and finer. On the west shore also there is little evidence of cliffing and shore retreat. This pattern of deposition is similar to that at Trapp's Cay and other cays in the central barrier reef lagoon; it is shown diagrammatically in Figure 42.

Below the undercut eastern shore, for the greater part of its length, is a ridge of hurricane shingle and rubble 10 yards wide and generally less than 3 feet high, enclosing arms and isolated pools of seawater. It is impossible to tell how much these ridges have altered since their construction in October 1961. Apart from the shingle carpets and ridges, there are few other visible effects of Hurricane Hattie; a handful of coconut trees have fallen, but apparently under the influence of wave rather than wind action, since they are all close to the shore. The cay is uninhabited and no beachrock or similar material was seen.

Colson Cay

Apart from its rather different shape, Colson Cay (Figure 42) perfectly reproduces all the features of Scipio Cay. The two islands are only one mile apart, and separated by 14 fathoms water. Colson Cay is triangular, 190 yards long, with a maximum width of 150 yards; the greater part is low and sandy, with a dense vegetation of coconuts, with *Thrinax*, *Cordia*, and grasses, enclosing a large central area of *Avicennia* marsh and standing water. Like Scipio Cay, the old shore has been subject to undercutting on the southeast side, and hurricane shingle has been deposited both on the cay surface and in front of the cliff as a separate ridge, enclosing pools of seawater and low-lying shingle spreads. The shingle carpet on the old cay surface is generally about 20 yards wide, and rises to a maximum height of 4 feet above the sea. The shingle spread below the cliff is 15-20 yards wide, and the outermost shingle ridge is 2-2½ feet high. At the extreme southeast point this ridge is itself now being destroyed by wave action, flushing out the fine material to leave a lag of larger *palmata* slabs. The material on the west shore is finer than that on the east. Very few trees are down, and those noted indicate S-SW winds. On the east shore the shingle has invaded a stand of *Thrinax* most of which are still standing. Changes on the north side are very slight, though even here there is a thin deposit of sand overlying the old surface.

Bugle Cay

The intensity of hurricane change at Bugle Cay, compared with the mainly constructional physiographic and very slight vegetational changes at other cays in the Placencia Triangles, is at first sight surprising, but provides yet another illustration of the increased liability to catastrophic damage of islands, whose natural vegetation has been cleared for human occupation. Only the western end of the island is free from mangrove (Figure 43): here there is an arcuate strip of low sand 160 yards long and 15-50 yards wide, covered with coconuts with no under-vegetation. The present steel-frame lighthouse dates from 1951; there are also the brick remains of a former lighthouse, and the lighthouse keeper's wooden house. Unfortunately the cay was not visited before the hurricane, and this account of change is derived from a post-hurricane survey and conversations with the inhabitants. Erosion of the shore was general on the west and south sides of the sand area: on the west side this is revealed by surface-sand-stripping, root exposure and combing, and shore-cliffing; on the south side the erosion has been much greater, and the former extent of the land is now revealed only by remains of the old lighthouse and

other buildings a short distance from the present shoreline. Retreat here has been at least 10-20 yards. Great damage was sustained by the mangrove, which was not only defoliated but much broken and swept away over a large area immediately adjacent to the sand strip. Between the sand area and high mangrove there is now an open muddy marsh with small Rhizophora seedlings and open water. At the same time as the sand strip was being eroded on its outer side, deposition of fresh sand was occurring to leeward, extending the sand area across the marsh by up to 15 yards. The remains of the old lighthouse were broken down, but the new light was undamaged. One house disappeared when the land under it was washed away; the main house was broken from its stilts and carried 60 yards due north by winds and waves before being deposited on the marsh surface. Since the hurricane a wooden causeway has been built across open water and mud to reach it, and it is still inhabited. Many coconuts are still standing, and those which fell had been cleared at the time of my visit in April 1962. The pattern of erosion and deposition, however, clearly indicate southerly winds.

At the time of my visit there was a 60 yard long fresh sandspit at the north side of the sand area, which appeared to be a post-hurricane construction.

Other barrier reef and lagoon cays

Placencia Cay (True Point Patience Cay of Speer, 1765, 23; Patience Brother Island of Jeffreys, 1775) is a mangrove island with a small area of strand vegetation and coconuts, located half a mile east of Placencia Point and village on the mainland coast. Rhizophora was defoliated and some coconuts felled, but otherwise there was no significant damage. At Placencia itself, considerable damage was caused by Hurricane Anna, 1961, when I had the opportunity to inspect changes on the same day. Minor damage was caused to buildings, many coconut trees were blown down, the whole village was inundated, and fresh sand carpets were piled round the shores. Similar changes occurred during Hurricane Hattie, except that house damage was more considerable; a more detailed account is outside the scope of this report.

Jeffreys also mapped the small mangrove islands at the mouth of Placencia Lagoon as The Virgins, a name not now used, and Speer commented on these "several small Kays ... at the mouth of a large lagoon, where there is plenty of Turtle passes morning and evening ... in the day you can get none" (1765, 23); regrettably the turtle have also become less numerous. These cays suffered heavy defoliation.

Harvest Cay, three miles to the south, is the "Hobbe's Kay" of Speer (1765, 23). This and other islands to the south, such as Palmetto Cay, are more properly barrier beaches, built of terrigenous quartz sand, backed by mangrove swamp, than true coral cays. Harvest Cay bears a dense vegetation of coconuts, Thrinax, and mangrove, with a tall undergrowth of Batis maritima, and Cladium jamaicense and other grasses. Landings were made at three points along the seaward shore, but no trace could be found of the so-called "Harvest Hill", "a small wooded, table-topped hill, 82 feet high to the tops of the trees, which is a good landmark" (West Indies Pilot, I, 467; and Vermeer, 1959, 28).

Cays of southern barrier reef

Twenty-three further cays were mapped in detail on the southern barrier reef and in the barrier reef lagoon in 1960 and 1961; they were all photographed from the air in 1961, together with a number of others not investigated in detail. After the hurricane they were again all photographed and observed from the air in 1962. Observation during these flights, and comparison of the air photographs, showed that virtually no change to either physiography or vegetation had occurred on any of these islands during Hurricane Hattie. Such changes as had occurred were all minor, and may or may not have resulted from the hurricane itself. The northernmost islands not affected by the hurricane were the three vegetated Silk Cays. These will not be discussed here, but it is worth noting that the name "Queen Cays" of charts is locally unknown. Winzerling (1946) alleges that the name of Queen Cays derives from the seventeenth century vessel Queen of Bohemia, and I regret having repeated this (in Carr and Thorpe, 1961, 167). According to Lieut. Smith, of the first Admiralty survey, "the Queen Cays ... were formerly named the Seal Cays (sic), now altered to prevent confusion" (1842, 732). The name Silk Cays, on the contrary, is given to no other island on this coast, is the only name known locally, and should be restored to charts in place of Queen Cays.

In the absence of any hurricane changes on these cays, they will not be discussed here, but will be described in a further paper now in preparation.


EDGE OF COASTAL SHELF
RENDEZVOUS CAY
MIDDLE LONG CAY
0 MILES 1
DEPRESSION
REEF
SHOAL AREA
MANGROVE

FIG. 29

FIG. 30

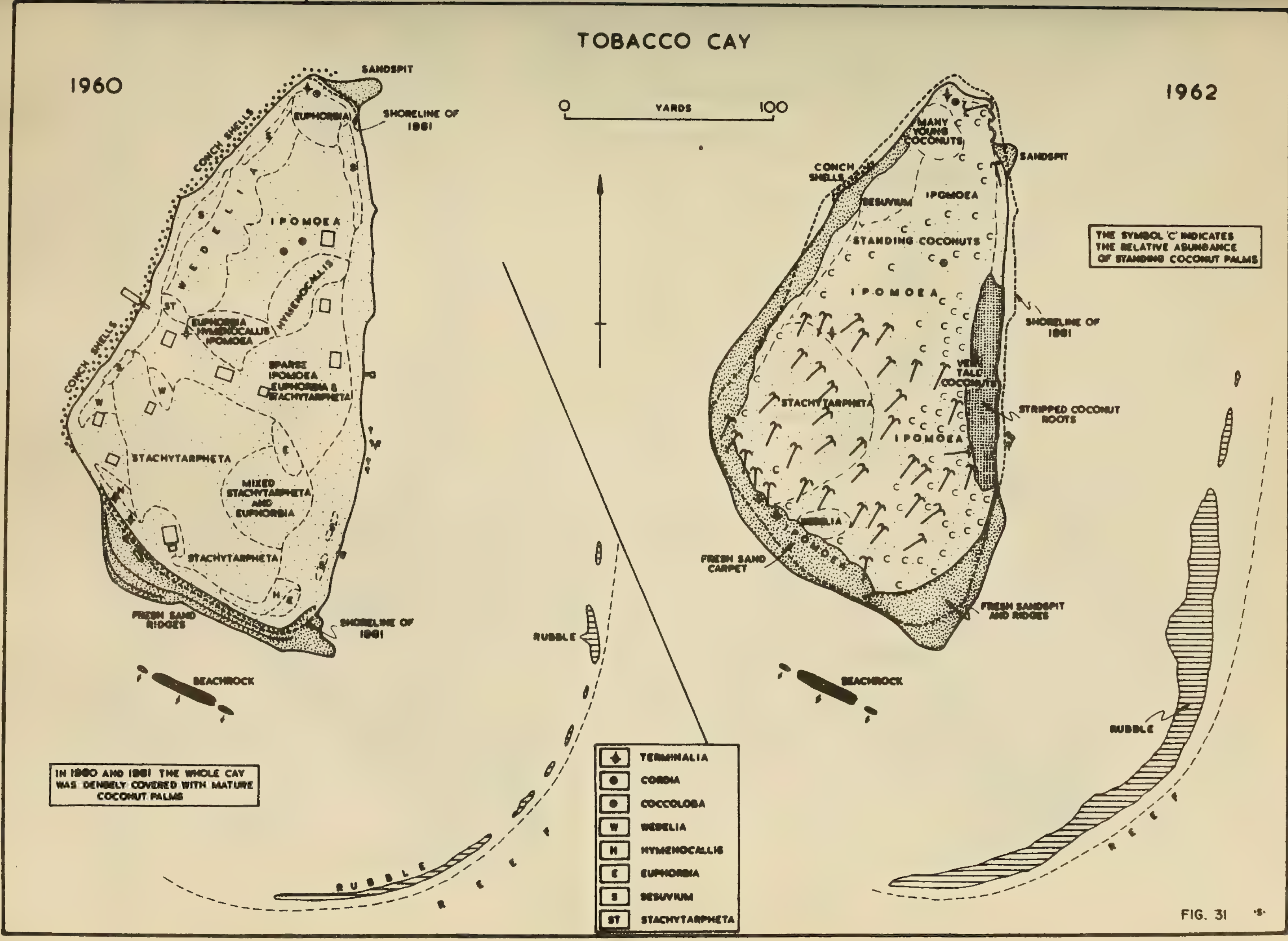

TOBACCO CAY
1960
1962
0 YARDS 100
SANDSPIT
SHORELINE OF 1961
CONCH SHELLS
EUPHORBIA
IPOMOEA
WEDELIA
HYMENOCALLIS
EUPHORBIA HYMENOCALLIS IPOMOEA
SPARSE IPOMOEA EUPHORBIA & STACHYTARPHETA
STACHYTARPHETA
MIXED STACHYTARPHETA AND EUPHORBIA
FRESH SAND RIDGES
BEACHROCK
RUBBLE
REEF
IN 1960 AND 1961 THE WHOLE CAY WAS DENSELY COVERED WITH MATURE COCONUT PALMS
MANY YOUNG COCONUTS
SESUVIUM
STANDING COCONUTS
VERY TALL COCONUTS
STRIPPED COCONUT ROOTS
WEDELIA
FRESH SAND CARPET
FRESH SANDSPIT AND RIDGES
THE SYMBOL 'C' INDICATES THE RELATIVE ABUNDANCE OF STANDING COCONUT PALMS
TERMINALIA
CORDIA
COCCOLOBA
W WEDELIA
H HYMENOCALLIS
E EUPHORBIA
S SESUVIUM
ST STACHYTARPHETA

FIG. 31

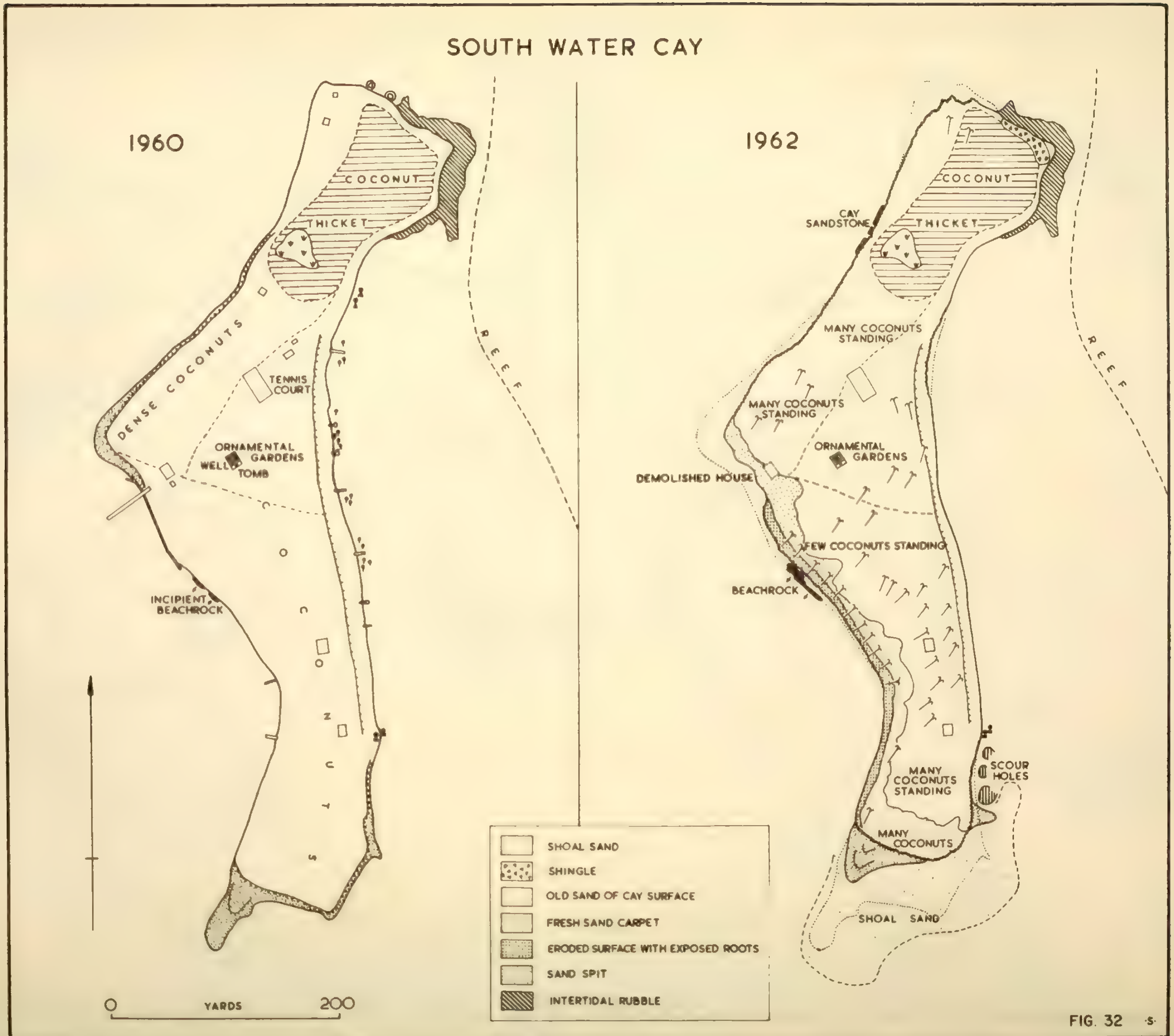
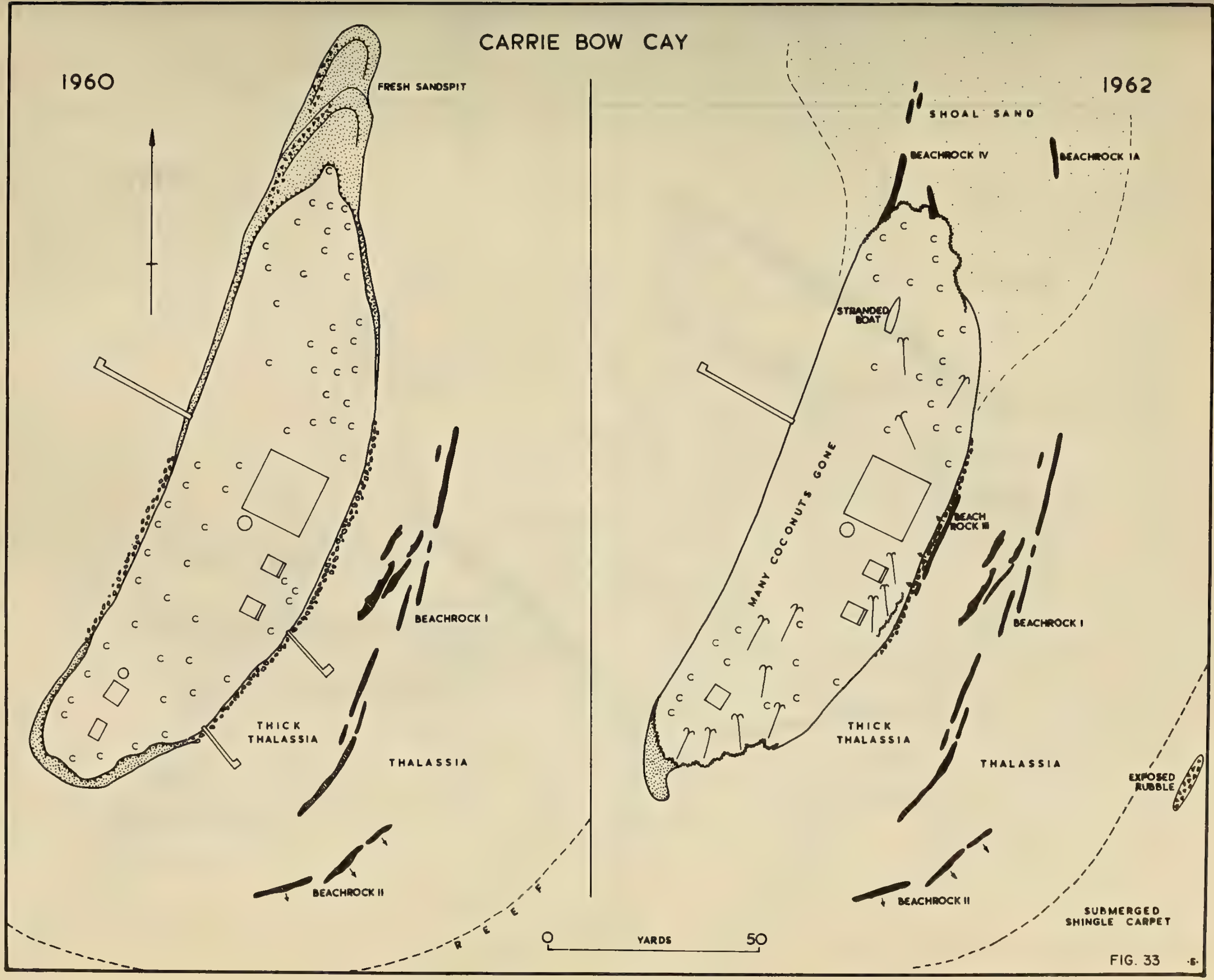

SOUTH WATER CAY
1960
1962
COCONUT
THICKET
DENSE COCONUTS
TENNIS COURT
ORNAMENTAL GARDENS
WELL
TOMB
INCIPIENT BEACHROCK
C O C O N U T S
REEF
CAY SANDSTONE
MANY COCONUTS STANDING
ORNAMENTAL GARDENS
DEMOLISHED HOUSE
FEW COCONUTS STANDING
BEACHROCK
MANY COCONUTS STANDING
SCOUR HOLES
MANY COCONUTS
SHOAL SAND
SHOAL SAND
SHINGLE
OLD SAND OF CAY SURFACE
FRESH SAND CARPET
ERODED SURFACE WITH EXPOSED ROOTS
SAND SPIT
INTERTIDAL RUBBLE
0
YARDS
200

FIG. 32 ·S·

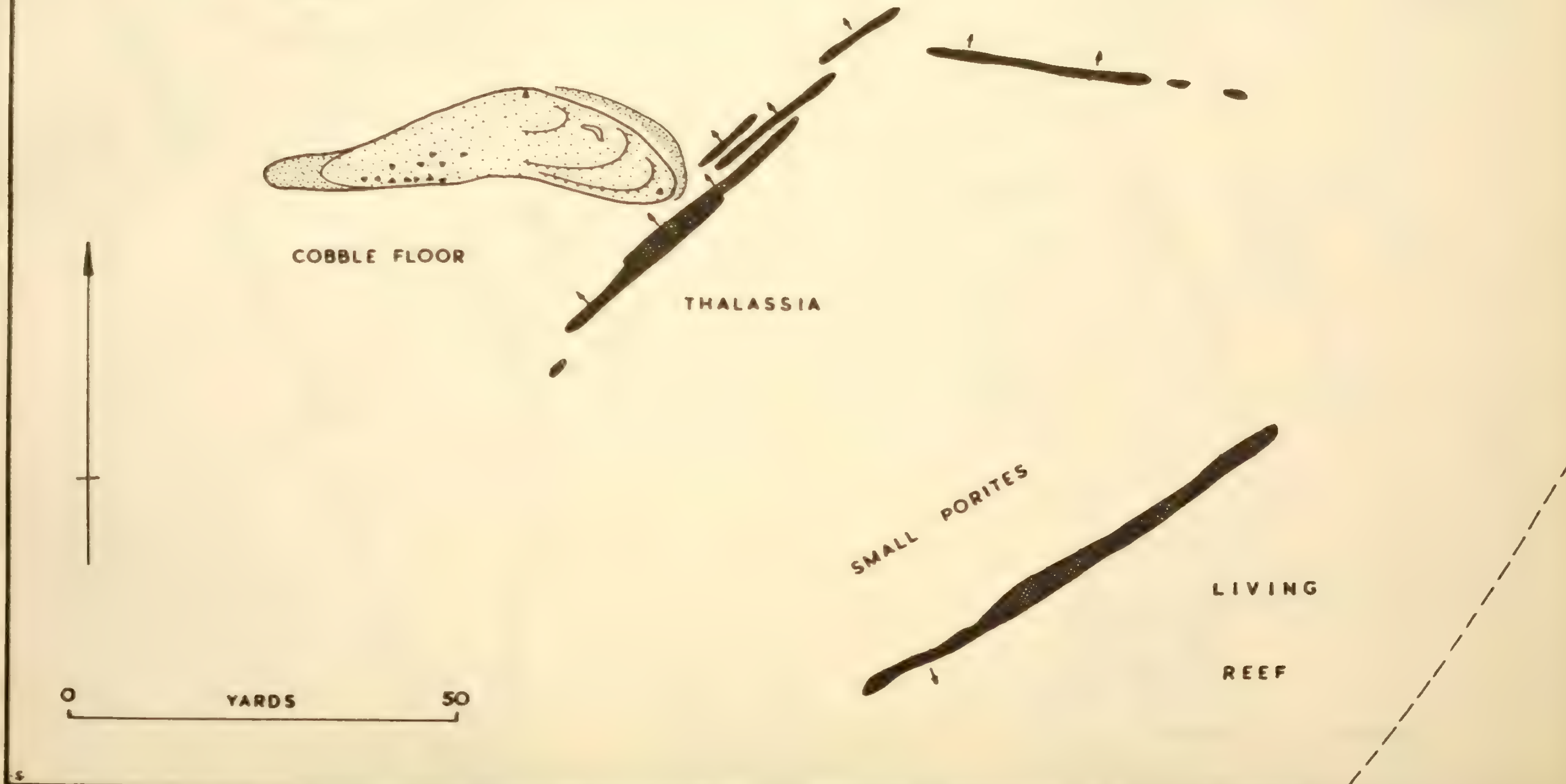


CARRIE BOW CAY
1960
FRESH SANDSPIT
BEACHROCK I
THICK THALASSIA
THALASSIA
BEACHROCK II
REEF
1962
SHOAL SAND
BEACHROCK IV
BEACHROCK IA
STRANDED BOAT
MANY COCONUTS GONE
BEACH ROCK III
BEACHROCK I
THICK THALASSIA
THALASSIA
EXPOSED RUBBLE
BEACHROCK II
SUBMERGED SHINGLE CARPET
0 YARDS 50

FIG. 33

FIG. 34

CURLEW CAY
1960




CAYS OF CENTRAL BARRIER REEF LAGOON
BASED ON ADMIRALTY CHART NO. 1797
SOUNDINGS IN FATHOMS
LESS THAN THREE FATHOMS
MORE THAN TWENTY FATHOMS
0
NAUTICAL MILES
5
STEWART CAY
BREAD AND BUTTER CAY
WEEWEE CAY
CROW'S NEST CAY
PETER DOUGLAS CAY
NORTHEAST CAY
SADDLE CAY
CAT CAY
MAN OF WAR CAY
QUAMINO CAY
CHANNEL CAYS
LAGOON CAYS
SLASHER SANDBORE
CRAWL CAY
ROUND CAY
TARPUM CAY
FALSE CAY
BAKER'S RENDEZVOUS
LONG COCO CAY
GLADDEN CAYS
FUNK CAYS
RENDEZVOUS CAY
JACK'S CAY
BUTTONWOOD CAY
WIPPARI CAY
SPIDER CAY
LARK CAY
CARY CAY
PLACENCIA CAY
ROUND CAY
TRAPP'S CAY
LONG CAY
BUGLE CAY
OWEN CAY
MOSQUITO CAY
HARVEST CAY
SCIPIO CAY
COLSON CAY
HATCHET CAY
LITTLE WATER CAY
SILK CAYS
LAUGHING BIRD CAY
ROUND CAY
POMPION CAY
GREAT MONKEY CAY
RANGUANA CAY

FIG. 35 ·S·

FIG. 36

BOTTOM TOPOGRAPHY IN PART OF CENTRAL BARRIER REEF LAGOON

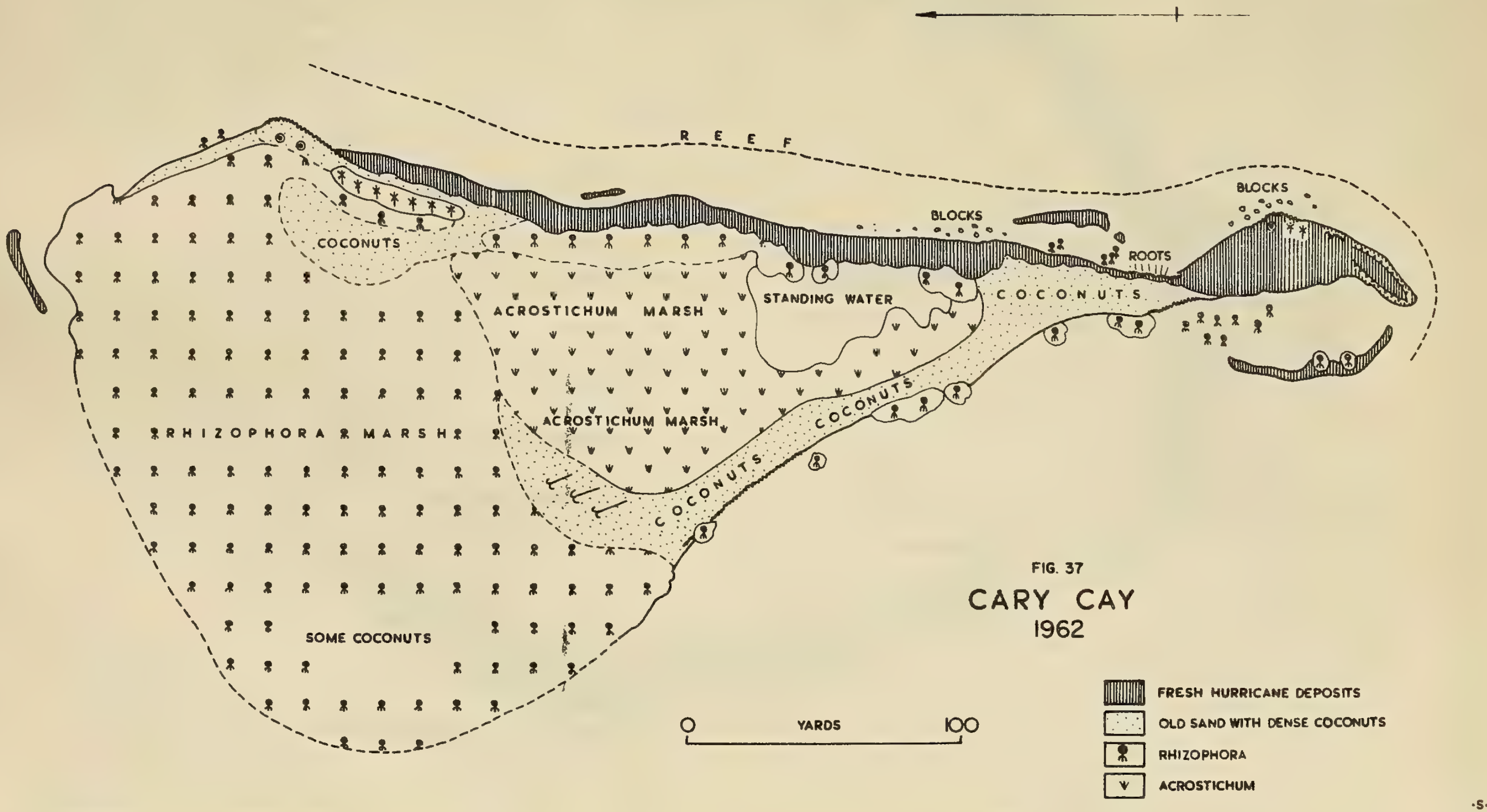
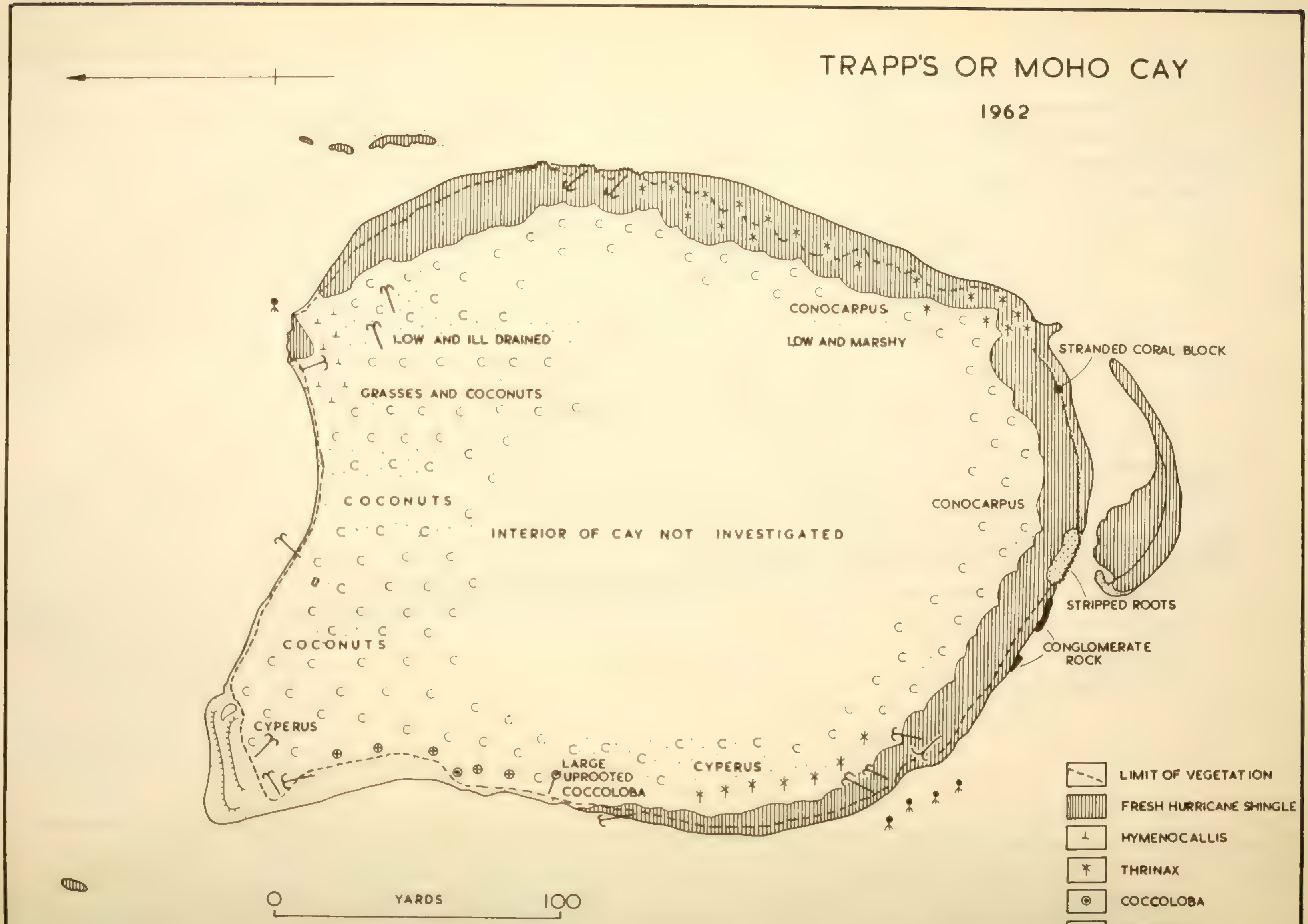


FIG. 37

CARY CAY
1962


TRAPP'S OR MOHO CAY
1962
CONOCARPUS
LOW AND MARSHY
LOW AND ILL DRAINED
GRASSES AND COCONUTS
COCONUTS
INTERIOR OF CAY NOT INVESTIGATED
CONOCARPUS
STRANDED CORAL BLOCK
STRIPPED ROOTS
CONGLOMERATE
ROCK
COCONUTS
CYPERUS
LARGE
UPROOTED
COCCOLOBA
CYPERUS
LIMIT OF VEGETATION
FRESH HURRICANE SHINGLE
HYMENOCALLIS
THRINAX
COCCOLOBA
THESPESIA
0
YARDS
100
·S·
FIG 38

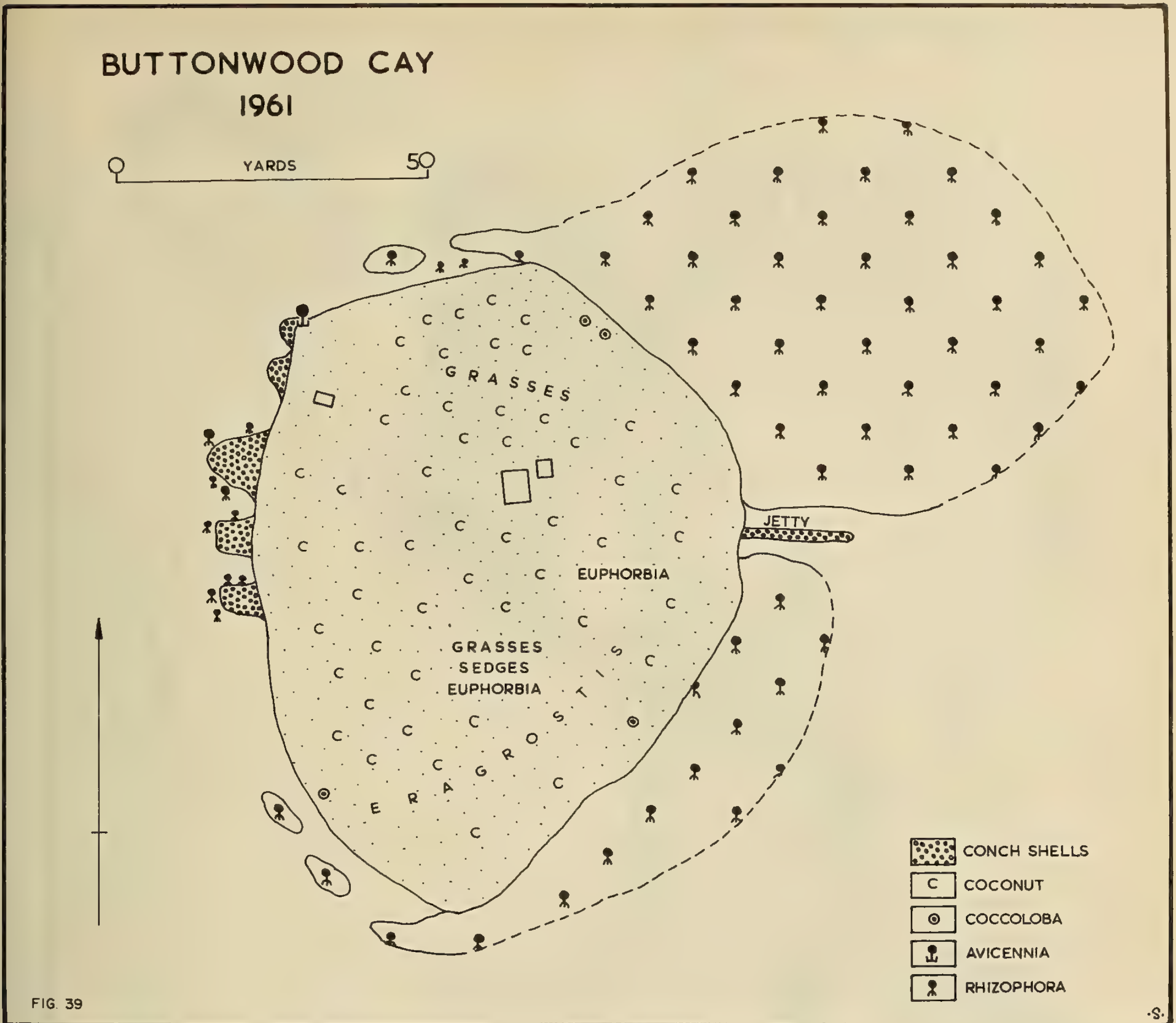

BUTTONWOOD CAY
1961
0
YARDS
50
GRASSES
GRASSES
SEDGES
EUPHORBIA
EUPHORBIA
ERAGROSTIS
JETTY
CONCH SHELLS
COCONUT
COCCOLOBA
AVICENNIA
RHIZOPHORA
C
·S·

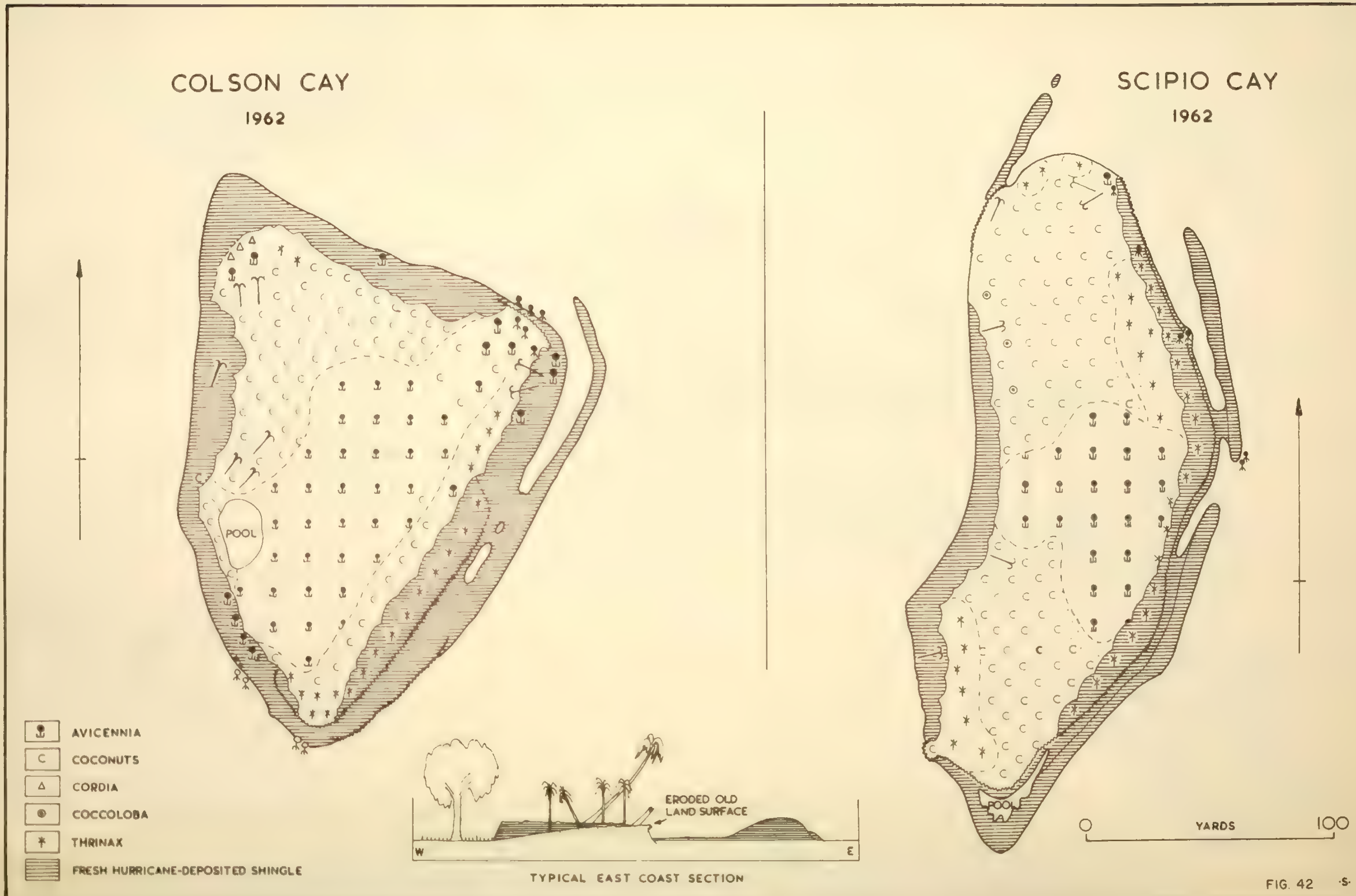
FIG. 39

FIG 40

LAUGHING BIRD CAY
1962

FIG. 41

OWEN CAY
1962



COLSON CAY
1962
SCIPIO CAY
1962
POOL
POOL
AVICENNIA
COCONUTS
CORDIA
COCCOLOBA
THRINAX
FRESH HURRICANE-DEPOSITED SHINGLE
ERODED OLD
LAND SURFACE
W
E
TYPICAL EAST COAST SECTION
0
YARDS
100

FIG. 42 ·S·

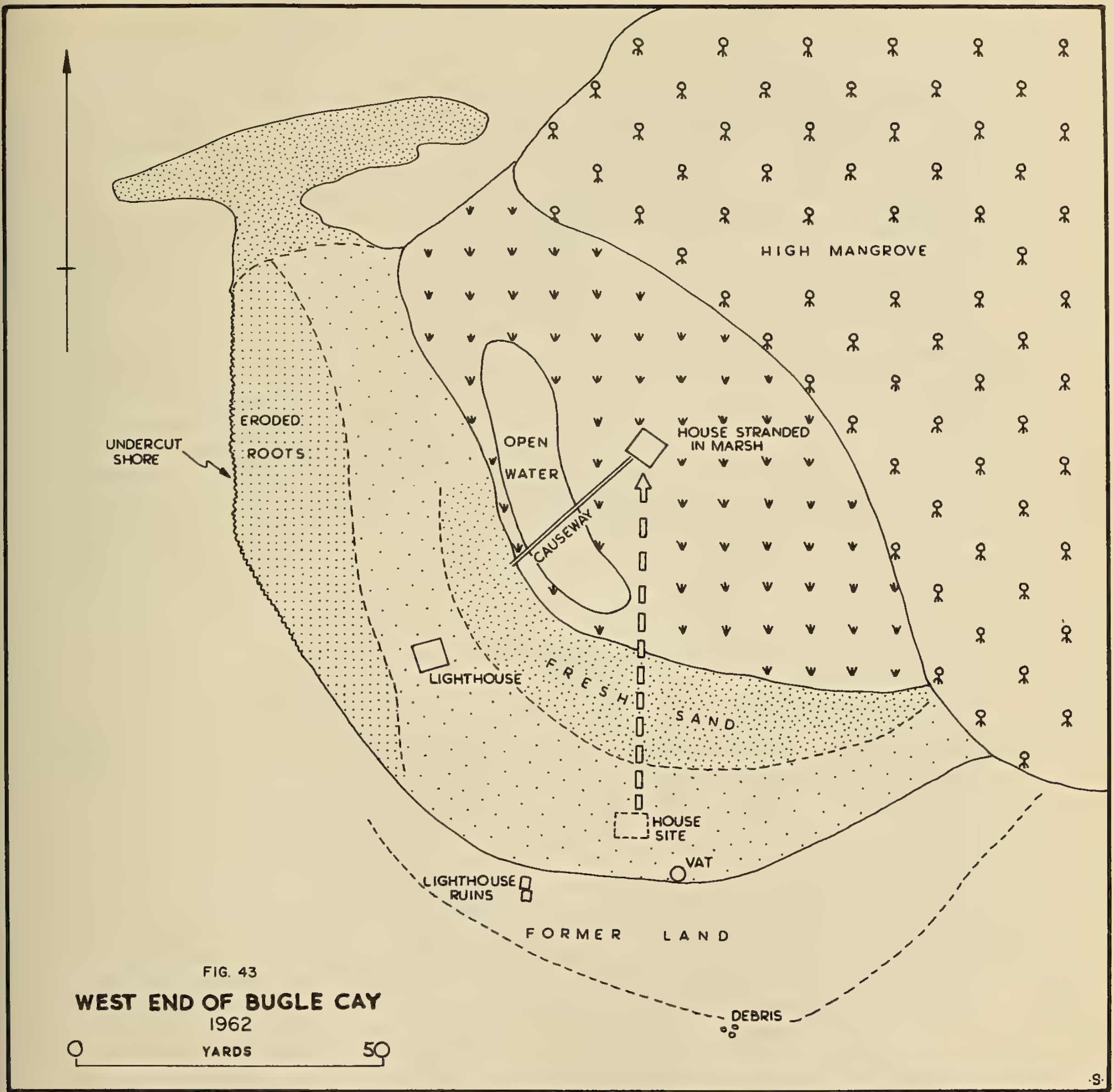


FIG. 43

WEST END OF BUGLE CAY

1962

VI. HURRICANE DAMAGE ON TURNEFFE ISLANDS

Turneffe Islands consist of a group of mangrove cays on a shallow reef-fringed bank 30½ miles long and 10 miles wide at its maximum extent. The mangrove forms a rim on both east and west sides of the bank, enclosing two shallow lagoons with depths of 1-3 fathoms. Much of the more exposed eastern side of the mangrove rim is fringed by a sand ridge, intermittently developed between Big Cay Bokel and Northern Entrance, and covered with coconuts. A number of small sand and shingle cays have been built at reef gaps along the narrow eastern reefs. Apart from these and the eastern sand ridge, the whole land area of the bank is mangrove, mud, and open water. For a fuller description, see ARB 87, 31-49, Figures 14-26. Hurricane Hattie crossed Turneffe diagonally, from approximately Pelican Cay, 17°24'N, on the east side, to between Crickozeen and Ambergris Creeks, about 17°22'N, on the west side. According to the report from Cay Bokel (Chapter 2) the eye of the hurricane extended sufficiently far south to be experienced for a few minutes at this point; this may indicate a more southerly motion in the channel between Turneffe and the barrier reef. The extent of hurricane damage is here described for individual cays from north to south. The Northern Cays, the Cockroach Group and Pelican Cay lie to the north of the storm track; all the rest lie to the south.

The Northern Cays

North of the main mass of the Turneffe lagoon mangroves are three larger cays: Three Corner Cay, Crawl Cay, and Mauger Cay. Mauger Cay is the northernmost, a long narrow mangrove island, oriented east-west and slightly convex northwards. The central part has been cleared, and when visited in 1960 was low and sandy, with prominent clumps of *Rhizophora* along both its north and south shores. There were at this time several houses and a 64 foot high lighthouse, built in 1885, on this central section, which was bounded along its northern shore by a thick masonry wall. There were less than a dozen coconuts on the cleared area, which did not rise more than 2 feet above sea level; *Batis maritima* covered most of the area, with *Sesuvium*, *Ageratum maritimum* and *Cyperus planifolius*. The lobes of the cay consisted entirely of *Rhizophora*, with no dry land. Hurricane Hattie caused severe damage. The mangrove was completely defoliated, and some clumps along the north shore disappeared. The masonry wall bounding the dry sand area was broken, and sand scoured out on the landward side. Coconuts and other strand vegetation were removed, surface sand was stripped, leaving a low-lying ill-drained surface at or only slightly above sea level. Shallow channels were cut through this surface on either side of the lighthouse, and fresh sand was deposited in the southern bay. All houses disappeared, though the lighthouse stood. In early 1962 the cay was no longer inhabited, and the lighthouse, though still in working order, was no longer functioning.

Three Corner Cay is a large mangrove island, shaped as its name implies, with a small dry land area near its eastern point. This was formerly covered with low coconuts. After the hurricane there were signs

of inundation, in sand stripping and root-combing, but most of the coconut trees were still standing. Direction of tree fall varied from 190 to 310°, indicating generally easterly wave directions. Most of the pre-existing ground vegetation must have been swept away; in May 1962, there was only a very sparse covering of Euphorbia and Ageratum.

Crawl Cay, the westernmost of the three northern cays, also suffered least damage; it consists entirely of mangrove, which in April, 1962, was already beginning to bear new leaves.

The Cockroach Group

The name Cockroach Group has been applied to a line of 28 islands, mostly sand and mangrove cays, on the east side of Turneffe, north of Northern Bogue. Cockroach Cay is the largest island in the group, and the only one inhabited when mapped in 1960. The cays between Cockroach Cay and Dogflea Cay were also seen at close quarters at this time; but those south of Cockroach Cay were known only from low-altitude air photographs. After the hurricane Cockroach Cay was re-mapped, and two other cays to the north were also mapped; all the rest were again photographed from the air.

Dogflea Cay, the northernmost of the group, lacks mangrove altogether. Before the hurricane it was a small island, perhaps 30 yards in diameter, with a cluster of coconuts and a dense undergrowth of bushes, probably Suriana and Conocarpus. This island disappeared during Hurricane Hattie, and now exists only as a sand shoal.

Pelican Cay (Figure 44) is a larger island immediately south of Dogflea Cay (Cay II of the Cockroach Group in Figure 24, AMB 87); it was visited for the first time in May 1962. Before the hurricane it had been a mangrove-sand cay, with coconuts, Thrinax, and stands of Cordia sebestena and Bursera simaruba on the sand area, which probably rose to a height of 4-5 feet above sea level. The leeward shores were fringed with mangrove. The physiography of this cay probably closely resembles that of most other cays in the Cockroach Group. The grouping of species in the tree cover is very marked: in the northeast mainly Bursera, much entwined with Ipomoea tuba; in the southwest, only Cordia. The island itself is nearly 150 yards long and 75 yards wide. When visited in May 1962 the highest parts were along the northeastern side, where fresh hurricane shingle was piled up to a maximum height of 7 feet above sea level, its steep-sloping inner edge abutting against a thicket of Thrinax palms. Southwards the height of the fresh shingle spread decreases, at the same time widening from 20 to 50 yards. While along the north shore the surface is undoubtedly higher than before, along most of the east shore there are two zones to be distinguished: an outer zone of erosion and inner one of deposition. The outer zone is revealed not in the usual way by exposed roots and undercutting, but by upstanding remnants of conglomerate rock, presumably formed beneath the previous surface. The rock is cavernous, formed of coarse coral shingle with individual fragments up to 12 inches long, weakly cemented with a brown sandy cement. The cementation, which recalls similar nearsurface cementation at Half Moon Cay (Chapter 7), is too poor for the

collection of specimens, but clearly sufficient to preserve the fragments against wave attack. The largest of the outcrops is 8 yards long and trends at right angles to the shore; at its seaward edge it stands 4 feet above the present shingle surface; its surface inclines slightly upwards inland; but at its inner edge the surface stands only 6 inches above the more steeply-banked shingle. The other main remnant is much smaller, but stands nearly 5 feet above the present sea level. The inner zone of deposition is evidenced by the invasion of Bursera and Cordia stands by fresh shingle. As elsewhere the Cordia is much more broken than the Bursera. Rhizophora has been completely defoliated, but a pair of Ospreys, Pandion haliaetus, were nesting here in 1962. The high bank of white shingle against the dark defoliated vegetation makes the cay distinctive from the seaward side.

Cay III disappeared during Hurricane Hattie, and Cay IV was stripped of vegetation.

Cay V (Figure 45) of the Cockroach Group, not previously mapped, is the next northwards to Cockroach Cay itself. It is similar in size to Pelican Cay, being 150 yards long and 60 yards wide, and it also consists of a seaward sand area, backed by leeward mangrove. The vegetation of the dry area consists mainly of Coccoloba, a few coconuts, Borrichia arborescens, Ageratum maritinum, and now dead unidentified bushes. The fresh shingle spread is here neither so wide nor so extensive as at Pelican Cay, nor has any cemented rock been exposed. The maximum height of the shingle is not more than 3 feet, and the width of the shingle spread is not more than 30 yards. The vegetation has been completely defoliated, but most of the branches remain in place.

Cockroach Cay itself (Figure 45) is a long narrow island, immediately north of a wide gap in the Turneffe east reef. In 1960 it was 310 yards long and 55-60 yards wide (cf. ARB 87, 46 and Figure 25). Its seaward shore for a distance of 180 yards was formed by a shingle ridge rising 3 feet above sea level, back of which the cay surface was composed of sand with scattered broken coral. The cay appeared to be extending northwards, and the northern section is mostly sandy. The vegetation consisted almost entirely of closely planted coconuts, with a few scattered stunted Cordia, and a ground cover of Euphorbia, grasses and sedges. There were numerous Rhizophora seedlings along the leeward shore, and at the southernmost point there was a thicket of dense Avicennia and Conocarpus. During the hurricane the coconut cover was almost entirely stripped; only five dead trunks remain standing. Few fallen trunks remain on the cay surface; most have been washed off the cay into the narrow back-reef lagoon. There has been slight backcutting along the whole of the seaward shore, especially at the northeast end, where retreat has exposed a few patches of poorly cemented sand at sea level. Here the shore is vertical, and formed of coconut roots; elsewhere it is lower and masked by coarse coral rubble. Much of the fresh sand at the north point has also been eroded away, leaving only a submerged sand shoal. On the cay surface there are generally three zones visible: an outer zone, with exposed, combed coconut roots, devoid of vegetation except for battered but recognisable Cordia, and littered with fresh debris; an intermediate zone, retaining some pre-hurricane surface vegetation, including patches of the old turf cover, but much littered with coral debris and with some exposed roots; and an

inner or leeward zone of thin rubble deposits, with patches of exposed roots. This rubble has in places slightly extended the leeward shore lagoonward. The Avicennia-Conocarpus thicket at the south end is much broken and now apparently dead. There has been some over-deepening of the floor between Cay V and Cockroach Cay.

Other Cays. The pattern of change on cays VII-XXVIII conforms to that described for Pelican Cay and Cay V. Leeward mangrove has been defoliated; windward bushes appear dead but remain in place, except close to the shore where they have been swept away by wave action or buried by a fresh shingle spread. Local and generally slight over-deepening has taken place between some of the cays. Some of the smaller islands (XI, XIX, XXV) have virtually disappeared.

Pelican Cay

Pelican Cay (not to be confused with Cay II, also so named, of the Cockroach Group) is a small island measuring 100 x 50 yards, situated $1\frac{3}{4}$ miles south of Northern Bogue (ARB 87, 44-45, Figure 23). In 1960 the whole land area was surrounded by a belt of Rhizophora, with a little Avicennia and Conocarpus; this rim was interrupted in only three places, two of them narrow boat-entrances lined with conch shells. The cay surface, then not more than 18 inches above the sea, was flat and featureless, built of grey sand, and planted to coconuts. In July 1961 the Rhizophora rim had been completely cleared from the northeast side. It was inhabited at this time by a Carib fisherman, and had two small huts; it is very similar in form and appearance to other Carib-inhabited cays of the barrier reef lagoon, such as Tobacco Cay and (southern) Rendezvous Cay. During the hurricane the huts were destroyed, all the coconuts felled and the sand area stripped of surface vegetation. The peripheral mangrove was all defoliated and much broken, and had not regained its leaves by May 1962.

Soldier and Blackbird Cays

Soldier and Blackbird Cays are located at the easternmost point of the east reef of Turneffe (ARB 87, 43-44, Figures 21-23). Soldier Cay is the larger of the two; before the storm it was 145 yards long, with a maximum width of 55 yards. The seaward, southeast-facing shore, 110 yards long, was formed of grey interlocking shingle rising to a fairly constant crestline 5.5 feet above the sea. From the crestline, the cay surface, consisting of fine grey sand with coral fragments, sloped gradually towards the lagoon, where the leeward beach, of fine white sand, formed a distinct ridge, especially at the north end of the cay. The seaward shingle ridge itself continued round the north end of the cay, and finer shingle was found for about 20 yards along the northern end of the lee shore. Only at the southern extremity was there any undercutting; but here the low cliff cut in grey sand was fronted by a fresh sandspit, 20 yards wide, already being colonised by vegetation.

Most of the original vegetation had been removed for coconuts, with the exception of low, spray-swept bushes of Tournefortia gnaphalodes, Coccoloba uvifera and Suriana maritima along the seaward shingle ridge and at the north end. There were patches of Sesuvium and Euphorbia along the ridge front, but apart from sparse Sporobolus the cay surface under the coconuts was bare. The coconuts themselves were about 40 feet high. Numerous Rhizophora seedlings were growing in shallow water along the west and south shores of the cay.

These salient features of Soldier Cay can no longer be recognised. The seaward shingle ridge has been destroyed, and fine surface materials scoured from the old cay surface to a depth of up to 2 feet. The surface now consists of a flat, low-lying area of exposed coconut roots, with scattered fresh white coral blocks, generally less than 1 foot diameter. The margins of the old island, which can still be traced as a distinct but low undercut cliff line, demonstrated marginal erosion on all sides of 5-10 yards, greatest at the north and south ends. At the south end the old spit of fresh sand has been swept away, and a number of pillar-like remnants of the old cay now stand some yards from the present shore. Along the east and west shores there has been considerable accumulation of fresh shingle. Along the east shore this forms a low, rather ragged carpet, extending from the old shore across the shallow and drying reef-flat on which the island stands. The seaward shoreline shown on Figure 46 is to some extent an approximation, since the carpet is so low and broken that it is difficult to say where the shingle ends and the sea begins. None of the shingle is higher than the eroded old cay surface. The hurricane deposits along the west side are much more extensive, forming a zone 25 yards wide and 85 yards long. The shingle is thrown up into two ridges, convex westwards, enclosing a low-lying zone between the ridges and the old cay. The ridges themselves have an average elevation of 2 feet but rise to 3 feet in one place. This is now the highest part of the island.

All except four of the coconut trees have disappeared, together with all the Tournefortia, Suriana, Coccoloba, Sesuvium, Euphorbia, and grasses of the old seaward shore. A single withered-looking Coccoloba has survived. The rest of the vegetation in May 1962 was probably a post-hurricane growth. It consists of a very scattered and sparse cover of Sporobolus, Cyperus, Ageratum, and a few patches of Portulaca oleracea. The coconuts which remain do not appear very vigorous. There are now no Rhizophora seedlings round the cay. The pier and all houses have disappeared, except that some house posts can still be seen at the extreme south end of the cay, which enables one to accurately superimpose pre- and post-hurricane maps in Figure 46. Seven people died here during the hurricane. Soldier Cay is now a bleak and desert place, almost devoid of soil, and unlikely to be resettled in the near future.

Blackbird Cay was situated about 100 yards NNE of Soldier Cay: a small, crescentic island, 70 yards long, formed of sand and shingle with larger coral slabs on the seaward side. Along the seaward shore were a number of mature Rhizophora and Avicennia trees, and the main part of the cay was covered with Conocarpus bushes, with three solitary young coconuts. The Rhizophora and Avicennia remain, but are now leafless and

apparently dead. The _Conocarpus_ and coconuts have been swept away, and the cay now consists of a rugged accumulation of coarse shingle and sand rising only a few inches above sea level.

Between Soldier and Blackbird Cays a crescentic ridge of fresh shingle and rubble, 30 yards long, has been formed near the reef crest. It is sharply asymmetric, with coral blocks up to 12 inches long on its seaward side, and fine shingle and sand to leeward. More shingle breaks surface to form a ridge immediately north of the Soldier Cay Elbow, and extends for 30-50 yards. Neither of these accumulations existed before the hurricane.

Calabash Cays

Calabash Cays are a group of four islands immediately south of Calabash Entrance on the Turneffe east reefs. Two of the cays are large islands (Big and Little Calabash Cays) and were formerly the centre of the Turneffe coconut industry (see ARB 87, 41-42, Figure 19-20).

Little Calabash Cay

Little Calabash Cay is the most southerly in the group. Before Hurricane Hattie it was regular in shape, with maximum dimensions of 95 x 60 yards. Along the seaward side a ridge of sand rose to a height of 2 feet above the sea; apart from this the surface was low, flat and featureless. There was a little undercutting along the northeast shore; but erosion on the south side had been retarded by the building of a pile-wall backed by conch shells. Conch shells were strewn along much of the cay beaches, and at the north end there was a 15-yard long peninsula of coconut husks. The island overlooked a reef flat, covered with _Thalassia_, and carrying only 6-8 inches of water. Immediately to leeward, however, the water deepened rapidly to give anchorage in 7-8 feet of water close inshore. Little Calabash Cay was the main clearing house for the Turneffe coconut trade. There was a long pier and warehouse, a small commissary, and dwelling houses. Coconut boats made regular runs into Belize, and the cay had its own wireless transmitting and receiving station. Natural vegetation had been almost entirely cleared for coconuts, except for a sparse ground cover of grasses and _Ageratum_.

The hurricane made great changes at this cay. The conch-shell ramparts and the southern palisades proved quite inadequate as a protection against hurricane waves, and along the northeast, east and southeast sides the shore retreated between 10 and 30 yards. The line of the much broken palisades can be traced some yards offshore (Figure 47); between the palisades and the cay the water is 1-2 feet deep. Scour holes along the old shoreline on the southeast side are 4-5 feet deep. Concrete blocks and wooden houseposts in shallow water indicate the former sites of houses. The cay surface has been much eroded; along the east side coconut roots are exposed and the shore is cliffed. Over the rest of the area, in spite of vertical erosion of about 1 foot, few roots are to be seen, but the whole area is now ill-drained, with a number of stagnant pools of water. A low fresh sand ridge 5-8 yards wide has been thrown

up along the southwest shore. The considerable erosion on the east side is balanced by deposition on the west. Here the jetty formerly stood in 7-8 feet of water for most of its length. Now the only sections to survive are terminal posts at each end: nearly the whole of the area between these posts is occupied by a peninsula of fresh sand, 25 yards long, and 40 yards wide across its base. The average thickness of this wedge of sand must be 5-6 feet. Immediately offshore the bottom falls away very steeply, so that within 3 feet of the shore depths of 1 fathom and probably nearly 2 fathoms are found. The outer slope of the sand peninsula must be comparable in steepness to outer slopes of fresh sand accumulations on land. Because of weather conditions it was not possible to investigate the reef conditions to seaward of the cay, but much of the _Thalassia_ flat had been buried by fresh medium shingle.

All houses and other installations have been destroyed. In May 1962 the only signs of habitation were house foundations, a solitary typewriter rusting on the sand, and quantities of lead from radio batteries. As an illustration of the extraordinary power of hurricane waves, the radio transmitter itself, measuring roughly 1 x 2 x 3 feet, a heavy object, was subsequently found near Harry Jones Point, having been transported approximately 3000 yards across water everywhere more than 1 fathom deep, and then lodged on a sandy surface, surrounded by vegetation 3 feet above the sea. The coconut trees have been completely destroyed. At the time of the re-survey there was a very sparse ground cover of _Ageratum_, _Wedelia_, _Cakile_ and grasses.

Big Calabash Cay

Big Calabash Cay lies some 300 yards northeast of Little Calabash Cay with which it is connected by a very shallow sandy reef-flat. The cay is aligned NNE-SSW, parallel to the reef, and is about 170 yards long (ARB 87, 42, Figure 20). Before the storm its width varied from 35 to 55 yards, and it was uniformly low and sandy. The maximum elevations were on the east side, where a sand ridge rose to 2-3 feet above sea level. There was no shingle on the island, but in several places the shore was marked by banks of conch shells. A spit of fresh sand extended 20 yards southwards from the main island. The whole cay was planted to coconuts, which formed a ragged canopy only 20-30 feet high. Apart from these, the ground surface was covered with grasses, both low, forming a turf, and taller, in scattered clumps. _Rhizophora_ seedlings were numerous close inshore, with taller _Avicennia_ near the north end. There were several houses on the island, one of them very substantial. The leeward bay gave anchorage in 4-5 feet, though some distance offshore, as the floor sloped gradually.

Damage during the hurricane was severe, but less so than at Little Calabash Cay. The whole of the seaward shore retreated from 2 to 12 yards, leaving a ragged undercut shoreline of tangled coconut roots. The leeward shore also retreated from 5 to 10 yards, chiefly through scouring by waves flowing over the cay and forming plunge holes on the lee side; these holes average 5-6 feet deep. The lee shore erosion has not left such an undercut and ragged shoreline as on the seaward side, except at the southwest end, and also where longer scour channels have

been cut at the northeast and southwest extremities. That at the southwest end cuts across the base of the former sandspit, a fragment of which survives on its south side; this channel is less than 1 fathom in depth. That at the northeast end extends along the whole of that side of the cay, and is initiated in a scour hole more than 3 fathoms deep, with vertical and in places overhanging sides within a few feet of the shore. Smaller scour holes have been cut in the cay surface, particularly near the north end, where one contains a few inches of stagnant water. One of the old conch shell peninsulas has survived the storm, but its position has shifted slightly and it is now an island.

Nearly all the coconut trees have disappeared; 5 are still standing, and a few fallen trunks near the north end show a fairly constant orientation of 320-330°. Over much of the surface, especially towards the lee side, however, the original ground vegetation has survived, and it is possible to recognise the position of old tracks through the turf cover between houses which have now disappeared. All the Rhizophora seedlings have been swept away.

East Cays One and Two

East and north of Big Calabash are two smaller islands. East Cay One was formerly separated from Big Calabash by a shallow channel only 14 yards wide, carrying up to 12 inches water, with many Rhizophora seedlings. The cay itself was small and round, 40-50 yards in diameter, with much coarse and blackened coral rubble along its east shore. Most of the island was flat and sandy and did not rise more than 3 feet above sea level. In 1960-61 the vegetation consisted of a dense bushy growth of Suriana maritima and Conocarpus erectus, with several low Rhizophora and taller Avicennia trees around its margin. There were two distinct clumps of coconuts, totalling less than a dozen trees, near the centre of the cay. During the hurricane shorelines retreated 5-10 yards round almost the entire margin of the cay; surface sand was removed, and the surface littered with fine-medium coral debris. It seems likely that some of the vegetation had been removed before the storm to build houses, since there were a number of new concrete house foundations near the cay centre in 1962. However almost all the pre-hurricane vegetation has been destroyed: a single coconut still stands, with two Avicennia trees and a small bush of Borrichia arborescens; the former dense growth of Conocarpus and Suriana has disappeared, except for a tangle of dead bushes. Much rubble is scattered along the seaward shore, and a shallow scour channel heads between this cay and Big Calabash.

Big Calabash East Two has suffered even more severely. It was located about 90 yards north of East One, and consisted of a narrow strip of land, 50 yards long and generally less than 10 yards wide, with some shingle at its east end. Most of the cay was low and sandy and did not rise more than 18 inches above the sea. It was prolonged westward by a fresh sandspit. Before the storm the vegetation consisted of a peripheral belt of Avicennia and Rhizophora, a central thicket of Suriana maritima and coarse grasses, and two or three low young coconuts. The island has been almost entirely destroyed: the peripheral mangrove still remain in position of growth, though defoliated and apparently dead, but

the area enclosed by them, formerly the cay proper, is now covered with 2-3 feet of water, and of the Suriana thicket there is no trace. Outside the mangrove the reef flat has an average depth of 1 foot. Towards the west end of the former cay, moreover, erosion has cut a definite scour channel, heading in a scour hole at least 6 feet deep, some 15 yards from the old windward shore, and extending with decreasing depth across the reef flat to leeward. This curious concentration of erosion on what was formerly one of the highest parts of the reef flat is of interest.

The Deadman Group

The Deadman Cays consist of five small islands on the eastern reef flat, four miles from the southern end of Turneffe (ARB 87, 37-40). The cays are numbered for convenience from south to north.

Deadman I

Before the hurricane Deadman I was 110 yards long and varied in width from 20 to 32 yards. The island is aligned transverse to the reef, immediately north of a large reef gap; it was everywhere low, but rose at its eastern end to not more than 3 feet above sea level. The eastern end consisted of small, rather blackened shingle; westward the proportion of shingle decreased, until at the west end it was composed entirely of fine sand, prolonged by a submerged sandspit for a further 10-20 yards lagoonward. Along the south shore cemented sands were exposed for nearly 10 yards; the soft and poorly indurated rock was horizontal and passed under the beach sand; the exposure was only a few inches wide and 3-6 inches above sea level. There were many Rhizophora seedlings along the west, southeast and north shores of the cay. The whole island was covered with coconuts about 30 feet tall, with a ground cover of Sesuvium, Euphorbia, Hymenocallis and grasses. At the low western end , the fresh sandspit was being colonised by Sesuvium and a couple of Tournefortia bushes. There was a single mature Avicennia at the eastern end.

Severe erosion occurred during the hurricane along the whole of the south shore (Figure 49). The large Avicennia at the east end stood, and enables one to accurately locate the two cays before and after the storm. Deposition occurred along the whole of the northern shore; hence the general effect is one of a northward movement of the cay. Surface sand has been stripped from the whole area, exposing combed coconut roots, littered with fresh debris. The greater part of the south shore is now formed by a vertical step of coconut roots from which most of the sediment has been flushed. The previously noted area of cemented sand is now exposed for a total of 75 yards round the cay shore, with a total width of $2\frac{1}{2}$ yards. The upper surface is horizontal but pitted and irregular in detail, and lies a little above high tide level. The cementation is irregular but generally weak; however, if better cemented the feature would closely resemble the wide conglomerate platform described at Half Moon Cay, Lighthouse Reef (ARB 87, 69-72) and the "promenades" found by Steers at Morant Cays, Jamaica (1940a, 1940b). There is no doubt that the Deadman I promenade has been formed at its present level under the

old cay surface and is not an uplifted beachrock: the state of cementation, inclusion of coconut roots, and comparison of exposures before and after the hurricane all demonstrate that it is a contemporary feature, simply exposed by erosion.

Rubble is strewn over the eroded cay surface, and blankets it completely along the north side; the maximum height towards the east end is 3 feet above sea level. The coconut cover has been destroyed, though ten damaged trees remain standing. Most of the trunks have disappeared, but a few remain, oriented 355-020°, indicating southerly winds and waves. The former fresh sand spit at the western end has disappeared, but may be beginning to reform. Little vegetation survives from before the storm: a few lilies (Hymenocallis littoralis) protrude through the shingle at the east end, and there are one or two Borrichia bushes near the centre. The Sesuvium patch at the west end survives in smaller form. Otherwise the island is unvegetated apart from very sparse Euphorbia, Ageratum and Cyperus.

Deadman II

Deadman II (Figure 50) lies 150 yards north of Deadman I; before the storm it was roughly circular, with N-S and E-W diameters of 80 yards. The seaward shore was composed of fine shingle rising to a crest 2-3 feet above sea level, from which the surface declined eastwards to the wide and sandy leeward shore. The leeward shore itself faced a shallow sandy bay with numerous Rhizophora seedlings. There was no mature mangrove on the cay apart from one or two tall Avicennia and Laguncularia racemosa on the leeward shore. The cay was planted to coconuts, but the undergrowth was not cleared. The upper beach was covered with Sesuvium and Euphorbia, with Sporobolus and other grasses on the leeward side, passing inland under a dense thicket of Conocarpus, Suriana and Borrichia. Tournefortia gnaphalodes was seen at one point on the northwest shore.

The cay suffered erosion on all sides during the hurricane, but especially on the east side, which retreated an average of 12 yards. Along most of this side a low-lying platform of soft promenade rock was exposed, with horizontal but pitted upper surface, containing coconut roots passing landward beneath a steeply undercut cay margin, also of coconut roots. One or two coconut boles, detached from the cay, are still standing near the east point. The composition of the promenade rock is variable: in the south it includes shingle, northwards it becomes almost clayey. Above the undercut eastern cliffline there is a narrow zone of stripped roots, followed inland by a blanket of fresh shingle piled against dead bushes and trees. The shingle has a maximum width of 25 yards and rises 2 feet above sea level. Its inner edge is arcuate and steep; the rest of the island is covered with dead bushes, with a little living Borrichia arborescens, Ageratum littorale, Sesuvium portulacastrum, Iresine diffusa, Cakile lanceolata, and Sporobolus. All the coconuts except eight have fallen, with directions indicating southerly winds and waves. All the peripheral Rhizophora is dead, and the Avicennia and Laguncularia have disappeared. Much rubble has been scattered over the nearshore area on the east side of the cay.

Deadman III

Deadman III (ARB 87, 38-39, Figure 18) was a small island 50 yards long and 35 yards wide before the hurricane. It was covered with a thicket of Conocarpus, Laguncularia, Avicennia and Tournefortia, with a few coconuts, and an undercover of Sesuvium, Ipomoea and Sporobolus. The coconuts have fallen and the bushes are all defoliated, but otherwise the changes at Deadman III have been minor. Fallen trees are oriented 320°, indicating winds and waves east of south. The formerly sandy surface is now covered with shingle.

Deadman IV

Deadman IV (ARB 87, 39) is the largest island in the group, and lies about 200 yards north of Deadman II. Before the hurricane it was oval-shaped, with maximum dimensions of 125 yards N-S and 95 yards E-W. The eastern shore was formed of low-lying rubble rather than shingle, and the island surface was generally sandy, especially towards the west side. The western bay was very shallow with many Rhizophora seedlings and mature Avicennia along the shore. On the island the vegetation cover was dense and difficult to penetrate. Much of the seaward shore was lined with a hedge of Tournefortia, backed by Coccoloba thicket; elsewhere the upper beaches were covered with Sesuvium, Euphorbia, Sporobolus and other grasses. The centre of the cay was covered with a palm thicket, with coconuts and Thrinax.

Erosion was severe during Hurricane Hattie on all sides of the island except the north (Figure 51). The amount of retreat is shown, for example, by the now nearshore remnants of the Coccoloba thicket on the southeast side. All the vegetation on the windward side - Tournefortia hedge, Euphorbia, Sesuvium - has been destroyed, and the eastern half of the cay is blanketed by fresh shingle up to 30 yards wide. The inner edge of this carpet reaches 3-4 feet above sea level. On the seaward side the old cay surface can only be seen at the southeast corner, where it forms an undercut cliff, mostly consisting of coconut roots, irregular in plan, with a single small area of cemented sand at its base. The western half of the cay is almost unrecognisable, both in plan and in vegetation. It appears to have been inundated and subjected to surface erosion; most of the vegetation has been killed and leaves and branches stripped, but much remains in the position of growth. Eleven coconuts are still standing with a number of Thrinax palms, and there is a fairly luxuriant ground cover of Ageratum, Euphorbia, grasses, and patches of Sesuvium. There is now only a handful of Rhizophora seedlings. The mature Avicennia and Laguncularia has disappeared. The great change in outline of the leeward shore may seem surprising, but it was previously very low-lying, and only a little sand re-distribution would be necessary to shift the shoreline considerable distances landward or seaward.

Deadman V

Four hundred yards north of Deadman IV lies the last of the Deadman Cays: Deadman V (ARB 87, 39-40). In 1960 it was a low-lying sandy island some 50 yards long, with a large area of Rhizophora to leeward. The cay was devoted to coconuts, with a very sparse undercover of Sesuvium, Cyperus and Sporobolus. There was some dead mangrove and small Rhizophora seedlings along the south shore, and a gnarled old Avicennia at the eastern point.

During Hurricane Hattie the dry land area suffered erosion on all shores with the formation of irregular undercut cliffs (Figure 52). Surface sand was stripped over about half of the area, with exposure and combing of coconut roots. The stump of the old Avicennia still stands at the east point. Roots are combed from south to north, and along the north shore there is one major inlet, presumably cut back by water pouring across the cay surface. Most of the coconut trees have disappeared; a few trunks on the cay surface are oriented 320-350°, indicating winds a little east of south. Between the exposed root zone and the much defoliated mangrove is an area of sparse Sporobolus and Euphorbia.

Cay Bokel

Cay Bokel before the hurricane was the southernmost cay of the Turneffe Islands (ARB 87, 35-37). It was triangular in shape with sides about 35 yards long, and was low and sandy. No part of the cay rose more than 2 feet above sea level. A single line of beachrock 55 yards southwest of the island indicated retreat toward the northeast. There was a semi-automatic lighthouse on the cay, built in 1944, and a large house. The lighthouse overlooked the foundations of a second light 7-12 yards offshore in water 1-2 feet deep, said to have been destroyed in the 1931 hurricane. A concrete seawall between this wreckage and the shore was also much broken and awash. Northwest of the standing lighthouse was the concrete base of yet a third, tilted and only partly exposed, said to have been destroyed in the 1945 hurricane. The cay was almost devoid of vegetation except for coconut palms: there was a patchy cover of Ambrosia hispida, and a few lilies, Hymenocallis littoralis. Before the hurricane there were some Rhizophora seedlings, but no mature mangrove.

During Hurricane Hattie the island disappeared, with the loss of six lives (Figure 53). The area of the cay is now covered with 4-5 feet of water, with 6-9 feet in places near the lighthouse. The light itself has fallen on its side, oriented 045°. The 1945 Lighthouse base has been completed exposed, with a large living Diploria adjacent to it. Across the middle of the old cay area there is a shingle shoal carrying only a foot of water, and shingle has also accumulated over a wide zone to south and southwest of the cay, without breaking surface. The jetty has disappeared, and all that remains of the vegetation cover is a single submerged coconut trunk. There is at present no sign of accumulation of sand to form a sandbore at this point; it seems unlikely, after so many losses due to hurricanes, that the present light will be re-erected here, and more probable that it will be transferred to the Turneffe "mainland" at Big Cay Bokel.

The Eastern Sand Ridge

The windward side of the eastern mangrove rim of Turneffe Islands is fringed for much of its length by a low, coconut-covered sand ridge. This extends from near Northern Bogue to Harry Jones Point, a distance of about $8\frac{1}{2}$ miles, though it is here generally separated from the eastern reef flat by a strip of Rhizophora. It extends discontinuously along the embayed east shore between Calabash Entrance and Grand Bogue; and again forms a long unbroken ridge on the south side of Grand Bogue, as far as Rope Walk. Its southernmost extent is found along the southeast-facing shore of Big Cay Bokel. For distribution details, see ARB 87, Figure 14. It is almost wholly sand, generally 3-4 ft in height near its seaward shore, and declines in height westwards to pass beneath the lagoon-fringing mangroves. It is wholly planted to coconuts, with an undercover of Hymenocallis, grasses, and prostrate plants, with intermittent patches of Tournefortia, Suriana and Coccoloba. The ridge is clearly similar in origin to the sand ridges along the windward sides of such barrier reef islands as Ambergris Cay and Cays Caulker and Chapel; but the fact that mangrove is often found to windward of it suggests that it may not now be an actively growing feature.

Lithified sands extending well above high water level have been described from the sand ridge at Harry Jones Point, Calabash Entrance (Dixon, 1956) and ascribed to a recent negative sea-level shift (Vermeer, 1959). The Harry Jones exposure was considered in some detail in ARB 87, 47-49, when it was concluded that because of its variation in height the rock could not be ascribed to eustatic movements, but may indicate tilting. After the hurricane, the whole eastern sand ridge was inspected from the air, and visited at a number of places. Several fresh outcrops of comparable lithified sands were found, which throw doubt on the interpretation of the Harry Jones rock as a true intertidal beachrock; and it now seems that these highstanding lithified sands can be explained without reference to any kind of eustatic or tectonic movements.

Fresh lithified sands were particularly noted at Big Cay Bokel, Grand Bogue Point, and Harry Jones Point.

Big Cay Bokel

Big Cay Bokel is a large mangrove island, some 900 yards north of Cay Bokel, forming the southernmost sector of the Turneffe mangrove rim. It is roughly triangular, with maximum N-S dimensions of 1 mile, and E-W width of two-thirds of a mile. The whole island consists of mangrove, except for a narrow strip facing the southeast reefs, and a small area at its north point, both of which consist of coconut-covered sand ridge. The southeast ridge is the longest, extending for about 1100 yards: for most of its length it is oriented N070°E. The ridge approaches closest to the eastern reef at its northeastern extremity, and diverges southwestwards, becoming lower, and eventually being separated from the reef flat by a narrow mangrove rim.

The south and southwest shores of Big Cay Bokel consisting wholly of mangrove, were devastated by the hurricane, and the Rhizophora is now leafless and apparently dead. On the lowlying sandy area, immediately in the lee of the mangrove fringe, many coconuts have fallen, oriented 020-030°. Along the sand ridge proper orientation of fallen coconuts

varies from 300 to 030°, with most 360-010°, indicating southerly winds. Between half and three-quarters of the coconuts have been felled; of those still standing, most have lost their crowns. The ground vegetation has not been destroyed, except close to the shore, where fresh sand has been deposited over a zone 15-30 yards wide. This suggests that damage resulted from storm waves only, and that the storm surge was insignificant here. Ground vegetation consists mainly of grasses and Euphorbia, with unidentified bushes. Broken coconut stumps and exposed roots along the shoreline indicate an unknown, but probably small, amount of shore retreat.

The ridge reaches its highest point, 2½-3 feet, at its northeast end. Here surface vegetation has been completely stripped from the near shore area, leaving only matted coconut roots and a few broken stumps. At this point, too, sand and fines have been flushed away, leaving only shingle. This point is closest to the east reefs, and thus most exposed to both constructive and destructive waves. Lithified sands are exposed for 25-30 yards near the point, and intermittently on the beach to the south and to the west. The sands form a ledge varying in width from a few inches to three yards, standing up to 2 feet above sea level. The upper surface is horizontal, and the rock is undercut at sea level on its seaward side. It is directly overlain by 12-20 inches of dense coconut roots at the point, with shells and shingle; and elsewhere by a gentle sand slope. The lack of surface hardening and erosion indicate that the rock was not exposed before the hurricane. Roots in the root zone can be followed directly into the underlying rock; and the whole horizontal surface of the lithified sands is marked by innumerable short segments of coconut roots, 2-3 inches long, protruding above the level surface.

This rock has clearly been formed beneath the old cay surface at its present elevation, and owes nothing to relative movements of land and sea. It is a cay sandstone (Kuenen, 1933, 86-88; Seymour Sewell, 1935, 502ff.) formed beneath the root mat, presumably at the water table, and exposed by the storm; it is quite probably being formed elsewhere beneath the surface of the Big Cay Bokel sand ridge at the present day. If case-hardened and weathered it would be indistinguishable from the Harry Jones lithified sands.

Grand Bogue Point

The sand ridge also outcrops at the shore, and was visited, immediately south of Grand Bogue, at Grand Bogue Point; it extends southwards from this point for about 3 miles to Rope Walk, but only the northern 600 yards could be investigated (Figure 54). Mangrove fringes each side of the Bogue proper, and the sand ridge only appears at its mouth. In its first 100 yards it rises from 2 to 4 feet above sea level, reaching 4 feet at its easternmost point, and then falls gradually southwards as the shore curves away into a large bay. The ridge is covered with coconuts, with a fairly dense ground cover of grasses and shrubs. The shore has evidently suffered some retreat during Hurricane Hattie. At the Point itself the shore is steeply undercut for about 170 yards, forming a steep cliff up to 4 feet high, capped with coconut roots, overlooking a very narrow beach and patchily overdeepened water. South of the Point,

where the ridge itself is lower, the undercutting is less apparent, but cemented sand is exposed slightly above sea level, the longest continuous exposure stretching for 100 yards. The exposure is intermediate in appearance between that at Big Cay Bokel, and at Deadman I and II; it is lower, but otherwise similar, to that at Harry Jones. It is at present rather poorly cemented and sandy throughout; in places near its southern extent it is almost claylike in texture, though generally harder. The upper surface is horizontal, though irregular, averages 9-12 inches above low water level, and its widest extent is 4 feet. It does not show the usual features of intertidal beachrock, such as seaward dip, and is probably better referred to as a promenade of cay sandstone, without necessarily implying any different origin.

A further point of interest is the occurrence, at the point itself, where the ridge reaches its highest point, of abundant Maya potsherds, in the upper few inches of the soil, entangled with coconut roots, and also scattered on the surface and on the narrow beach below the undercut cliff. The soil here is very black, and this very restricted area is much overgrown with the bush <u>Leucaena leucocephala</u>, by no means common on the cays. The pottery deposits, like the shore, formerly extended further seaward, and fragments are now found for some distance along the beach. All the material found was fragmentary earthenware, with the exception of a single obsidian blade. The crudeness of the pottery, paucity of obsidian, absence of constructional features, whole pots and jade, all contrast with remains on some of the islands of the southern barrier reef lagoon, to be described in a subsequent paper. Pottery from Grand Bogue Point is described by Mr. E.W. MacKie, Hunterian Museum, Glasgow University, who is familiar with mainland British Honduran pottery sequences, in Appendix 2.

<u>Un-named Point</u>

Air reconnaissance showed the existence of further "promenades" of slightly elevated rock similar to that at Big Cay Bokel and Grand Bogue Point, at a conspicuous point on the eastern sand rim 1 mile south of Calabash Cays. Unfortunately there was not time to visit this somewhat inaccessible location.

<u>Harry Jones Point</u>

Harry Jones (ARB 87, 47-49, Figure 26) was revisited after the storm; apart from very heavy destruction of coconut trees, the changes were relatively small. Direction of tree fall varies from 230-018°, the mean being about 300°, indicating southeasterly winds. Nearshore <u>Coccoloba</u> has also disappeared; much of the previously exposed "beachrock" has been destroyed; and at the point itself, retreat of the sand ridge has exposed fresh cemented material. Immediately north of the point, there are now two exposures of fresh rock, with horizontal upper surfaces standing $4\frac{1}{2}$ feet above sea level. The rock is still fairly soft, and the matrix contains coconut roots. At the inner edge, where the rock is covered by the sand ridge, these roots can be traced directly into the overlying root mat. This demonstrates quite conclusively that the rock is forming at its present altitude at the present time, and that it is not an

upraised beachrock exposed by negative movement of sea level or by warping of the Turneffe bank. As the fresh rock is followed southwards, its altitude declines, as before the hurricane, but its characteristics remain the same. At one point the rock was broken and found to contain a few fragments of Maya pottery, presumably of fairly recent age in geological terms; this too makes it unlikely that the rock dates from a high stand of the sea several thousand years ago. No other traces of Maya occupation could be found at Harry Jones, though the site is marked by Romney and others, 1959, Figure 10; it has probably been largely destroyed by shore retreat. The pottery was found exactly 200 yards south of the easternmost point, measured along the shore.

These new exposures show beyond doubt that the rock is an exposed cay sandstone, not a beachrock; hypotheses of eustatism or warping are therefore unnecessary. It is presumably a water table or percolation phenomenon similar to that described by Russell (1962); the decreasing height of the rock southwards simply reflects a lowering of the water table with a decrease in the height of the sandridge crest.

The beach was examined for $1\frac{1}{2}$ miles in the Harry Jones area without further features of interest being discovered. The previous steep shore has been flattened, and coconut roots exposed; inland from this erosion zone is a zone of deposition, especially on the east shore north of Harry Jones Point. Many coconuts have lost their crowns in this area. South of the point, into Calabash Entrance, the vegetation was previously denser, with fewer coconuts, and has survived better, in spite of its transverse alignment to major hurricane winds. Cordia was in flower here along the top of the beach in 1962. It was in this section that the Little Calabash Cay radio was found.

Turneffe Lagoon Mangroves

No systematic observations were made on the Turneffe lagoons and mangrove rims, and the following notes summarise miscellaneous points, some of considerable interest, noted during journeys through the lagoons and on aerial traverses. First, the supposed absence of reef-building corals from the interior lagoons must be corrected (ARB 87, 33). A small reef was discovered somewhat unexpectedly late one evening in Southern Lagoon; it lies approximately $1\frac{1}{4}$ miles due west of Small Fishing Bogue, and about $2\frac{3}{4}$ miles northeast of Shag Cay Bluff. The reef rose to within 2 feet of the surface from water more than 2 fathoms deep and consisted of *Montastrea annularis*, *Siderastrea siderea*, *Porites astreoides* and *Millepora*. Similar reefs are said to exist near Crickozeen, in the northern part of Southern Lagoon.

As in the barrier reef lagoon, the extent of mangrove defoliation and recovery provides some information on direction and strength of winds and waves. Thus defoliation has been most intense along the eastern rim, though even here small bushes of *Rhizophora* were bearing leaves on the western side early in 1962. Most of the small lagoon cays, as in Crayfish Range, are completely leafless. The western rim is less severely affected, though defoliation is total on its eastern or lagoonward side. As a result of defoliation and even disappearance of small mangrove areas on this western side of the lagoon, there is now great

difficulty in finding the lagoon entrance to creeks giving passage to the sea. In the creeks themselves, especially between Blue Creek and Grand Bogue Creek, defoliation was noticeably greatest and recovery least on the north side of each channel. The general impression, therefore, over the southern half of Turneffe, is one of southerly winds and waves. In the centre of the mangrove rims, defoliation has been less intense. Many trees have been blown down and one's impression is of devastation, but leaves are still growing. Presumably these areas escaped the inundation and intensive wave action which seem to have been responsible for the worst defoliation. Tree fall in the mangrove areas was worst in the area separating Northern and Southern Lagoons, over which the centre of the hurricane passed: trees have fallen in all directions and it is quite impossible to make out any dominant direction from the air.

It is clear that great quantities of water must have passed through the eastern bogues of the Turneffe lagoons under the influence of the storm surge and hurricane winds. This accumulation could only escape through the narrow, often winding western creeks. All of these have been overdeepened by scouring, but to an unknown amount. The overdeepened section of the creek is generally quite narrow with very steep and in places overhanging sides; the overdeepened channel itself meanders within the creek, and variations in depth are abrupt. At the western exits of the creeks there are now wide spreads of fresh sand, forming submerged deltas, together with scattered dead trees and bushes dumped by flood waters in shoal areas. The western rim itself was completely breached at one point a little less than 1 mile south of the exit of Grand Bogue Creek. The narrow, shallow western exits of Northern Lagoon were also widened and deepened, and small sand deltas were deposited on the west sides of all three gaps.

Crickozeen Creek Slumping

Finally, persistent rumours of an "earthquake" at Turneffe, coinciding with the hurricane, led me to visit the west side of the mangrove rim, immediately north of the outlet of Crickozeen Creek. Here, between the edge of the Turneffe bank and the mangrove rim, the floor is composed of fine, compact calcareous silt and sand, bound together with *Thalassia*. Two or three feet from the mangrove shore for a length of several hundred yards, there is a wide crack in the floor, here under only a few inches of water. The dislocation, up to several yards wide, has vertical sides and wherever tested was more than 3½ fathoms deep. It is arcuate in plan, and there are subsidiary smaller cracks both to the south and to seaward of the main crack. A short distance out into the bay the floor has been thrust up to form an area of shoal sand banks and emerged sand bores; the highest of these reaches 1½ feet above sea level, and they generally present a steep face towards the mangrove rim and a gentle slope to seaward. The general pattern of these features can be seen from Figure 55, drawn from an oblique air photograph. The best explanation seems to be that rotational slumping has occurred in these fairly cohesive sediments, presumably under the stress of extreme wave conditions in the partially enclosed bay to the north of Crickozeen Creek. I was unfortunately unable to investigate this area in any detail or to carry out a network of soundings; this feature seems to be unusual during hurricanes, and so far as I could ascertain, unique in the British Honduras area after Hurricane Hattie.

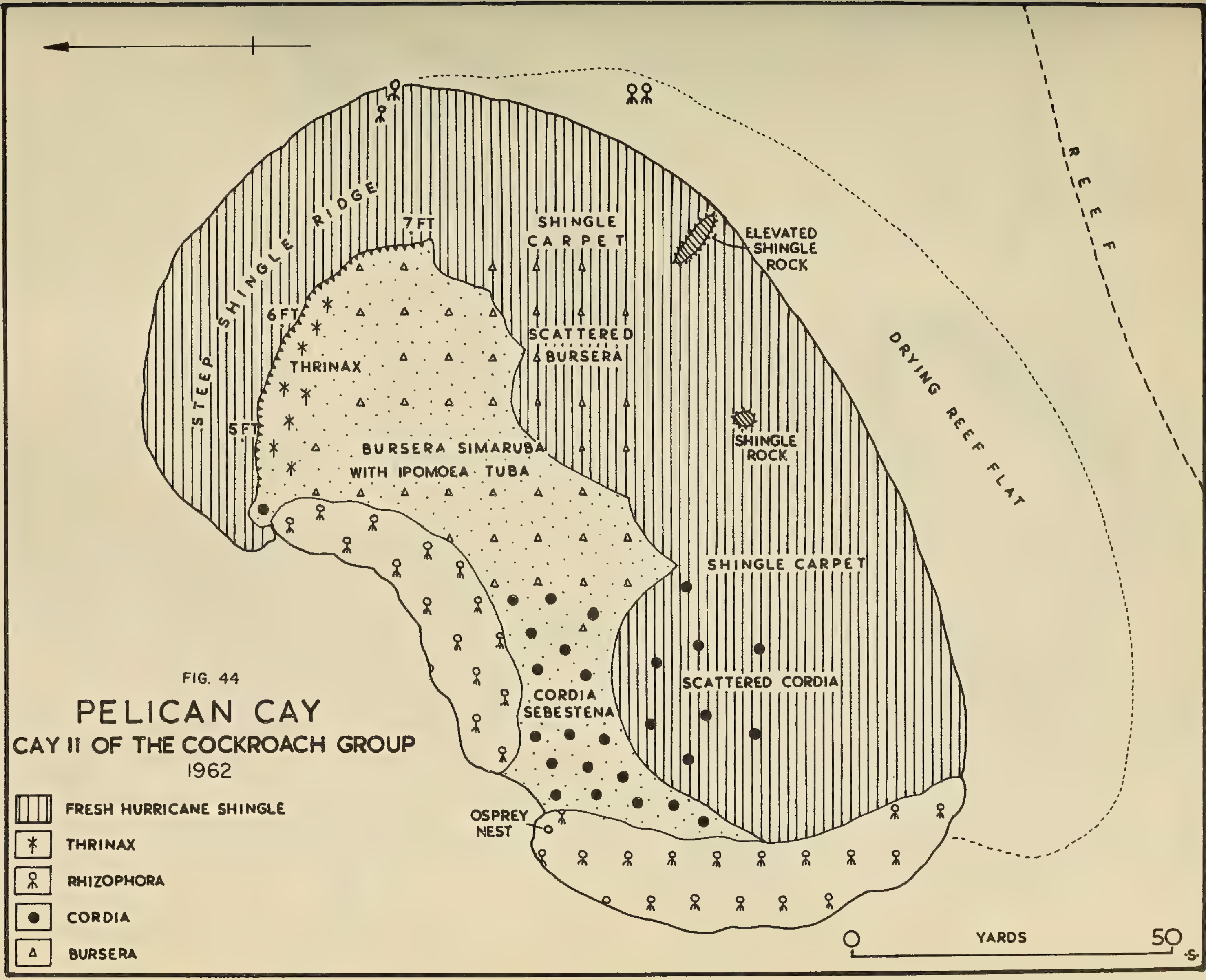


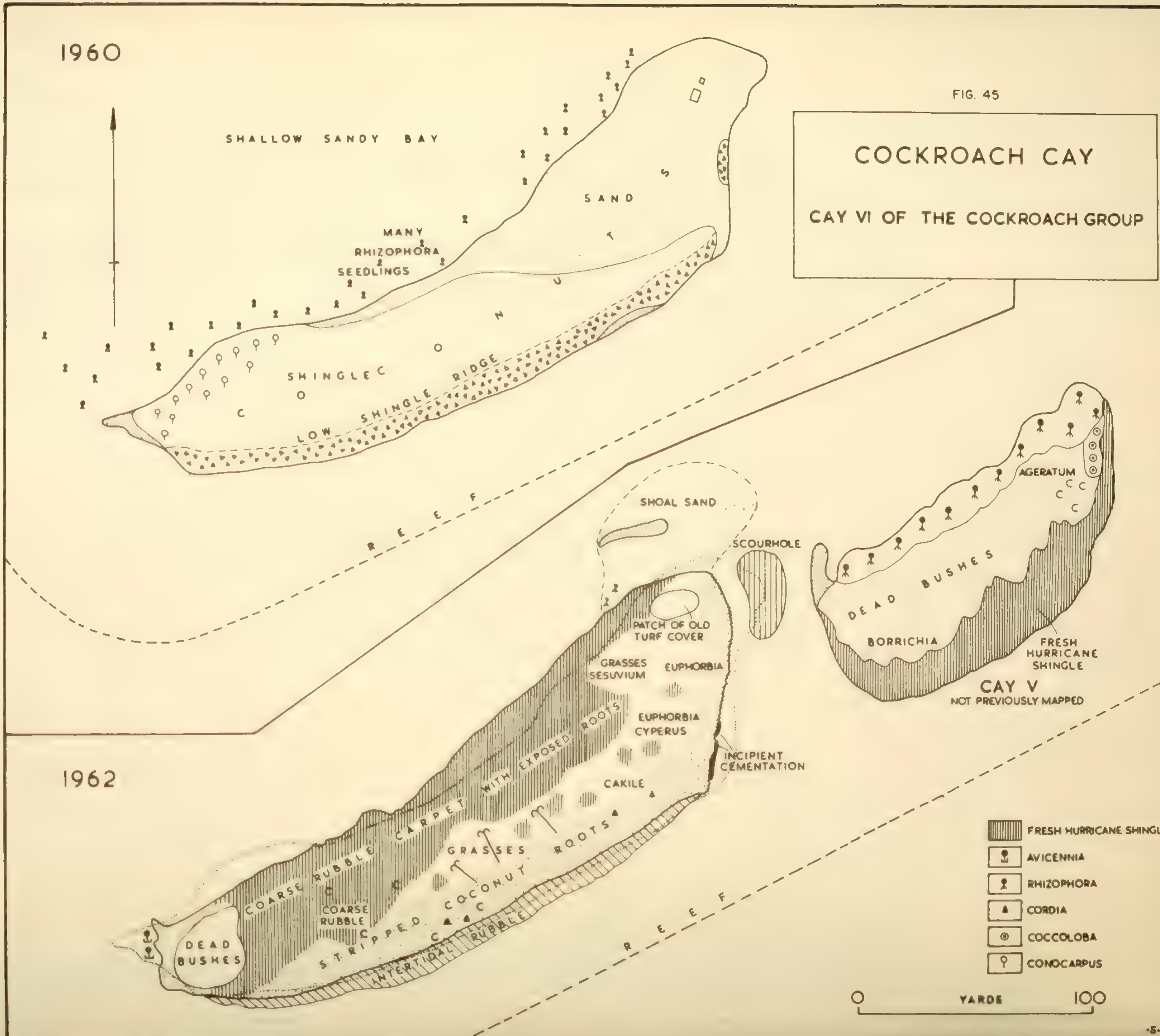
FIG. 44

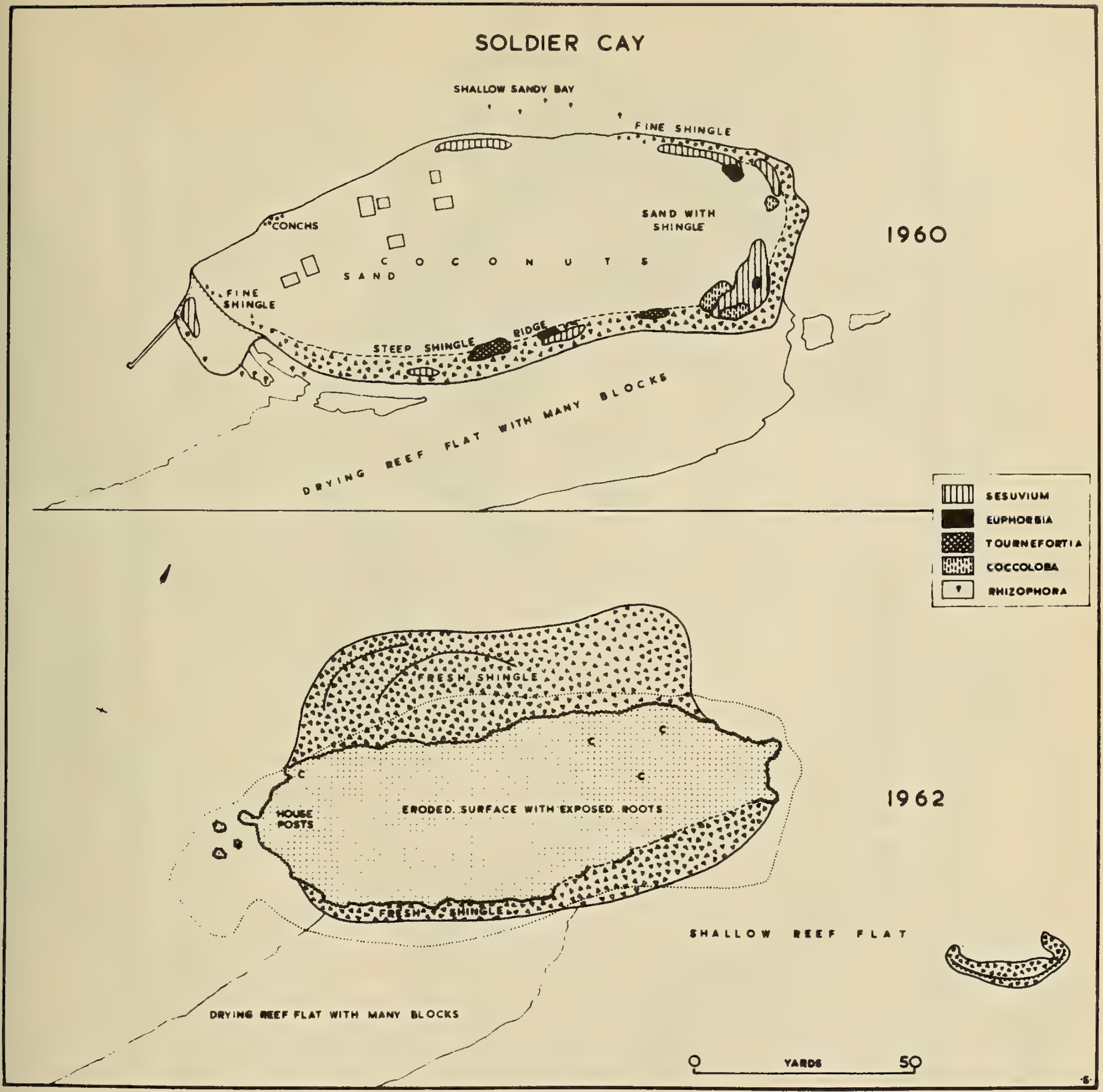
PELICAN CAY

CAY II OF THE COCKROACH GROUP

1962

FIG. 45


COCKROACH CAY
CAY VI OF THE COCKROACH GROUP
1960
SHALLOW SANDY BAY
MANY RHIZOPHORA SEEDLINGS
SAND
SHINGLE
LOW SHINGLE RIDGE
COCONUTS
REEF
1962
SHOAL SAND
SCOURHOLE
PATCH OF OLD TURF COVER
GRASSES SESUVIUM
EUPHORBIA
EUPHORBIA CYPERUS
INCIPIENT CEMENTATION
CAKILE
COARSE RUBBLE CARPET WITH EXPOSED ROOTS
GRASSES
ROOTS
COARSE RUBBLE
COCONUT
STRIPPED
INTERTIDAL RUBBLE
DEAD BUSHES
AGERATUM
DEAD BUSHES
BORRICHIA
FRESH HURRICANE SHINGLE
CAY V
NOT PREVIOUSLY MAPPED
FRESH HURRICANE SHINGLE
AVICENNIA
RHIZOPHORA
CORDIA
COCCOLOBA
CONOCARPUS
0
YARDS
100



SOLDIER CAY
SHALLOW SANDY BAY
FINE SHINGLE
CONCHS
SAND WITH SHINGLE
1960
C O C O N U T S
SAND
FINE SHINGLE
STEEP SHINGLE RIDGE
DRYING REEF FLAT WITH MANY BLOCKS
SESUVIUM
EUPHORBIA
TOURNEFORTIA
COCCOLOBA
RHIZOPHORA
FRESH SHINGLE
HOUSE POSTS
ERODED SURFACE WITH EXPOSED ROOTS
1962
FRESH SHINGLE
SHALLOW REEF FLAT
DRYING REEF FLAT WITH MANY BLOCKS
0
YARDS
50

FIG. 46

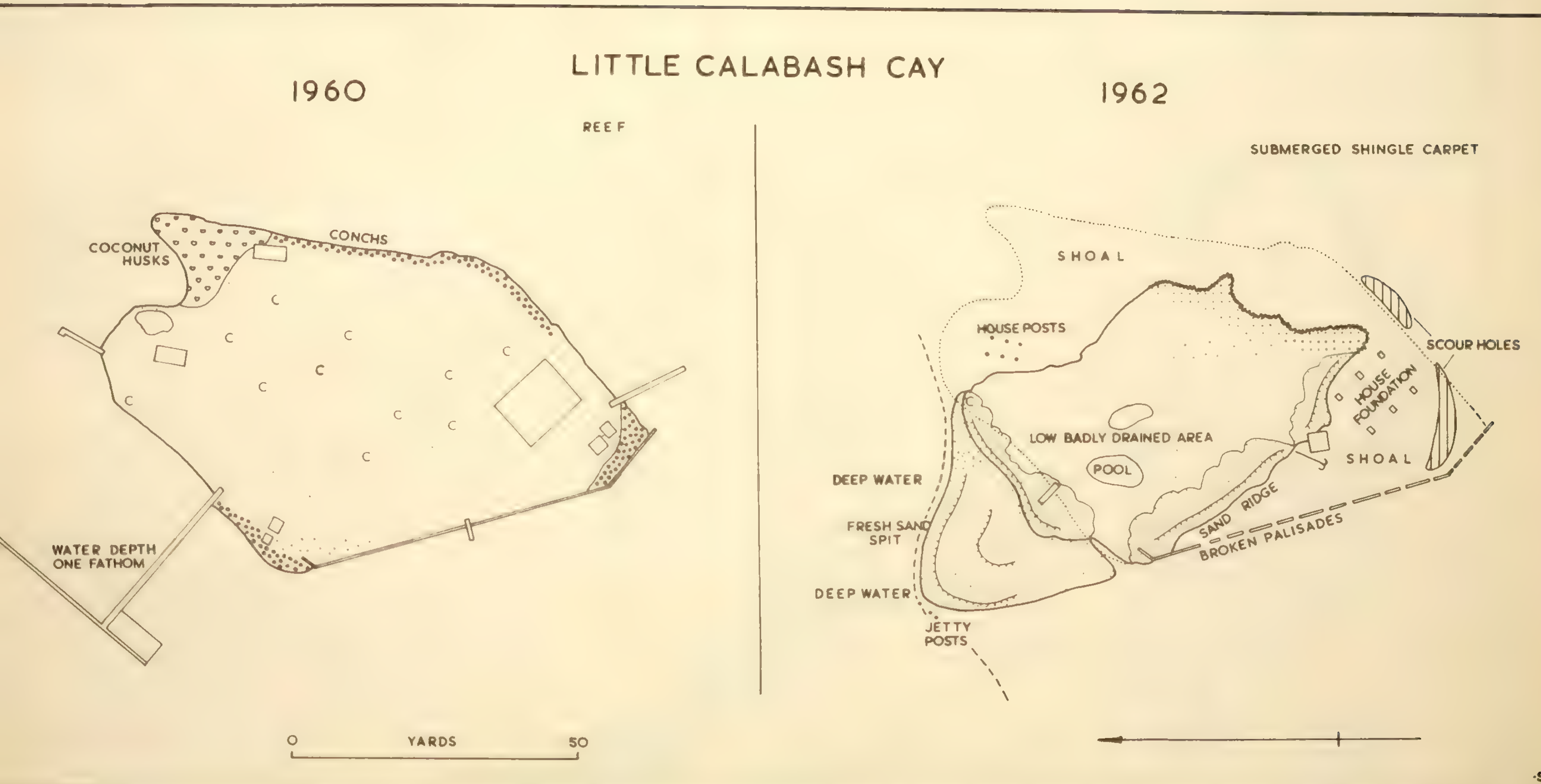

LITTLE CALABASH CAY
1960
REEF
CONCHS
COCONUT HUSKS
WATER DEPTH ONE FATHOM
0
YARDS
50
1962
SUBMERGED SHINGLE CARPET
SHOAL
HOUSE POSTS
SCOUR HOLES
HOUSE FOUNDATION
LOW BADLY DRAINED AREA
POOL
SHOAL
DEEP WATER
FRESH SAND SPIT
DEEP WATER
JETTY POSTS
SAND RIDGE
BROKEN PALISADES
S

FIG. 47

BIG CALABASH CAY

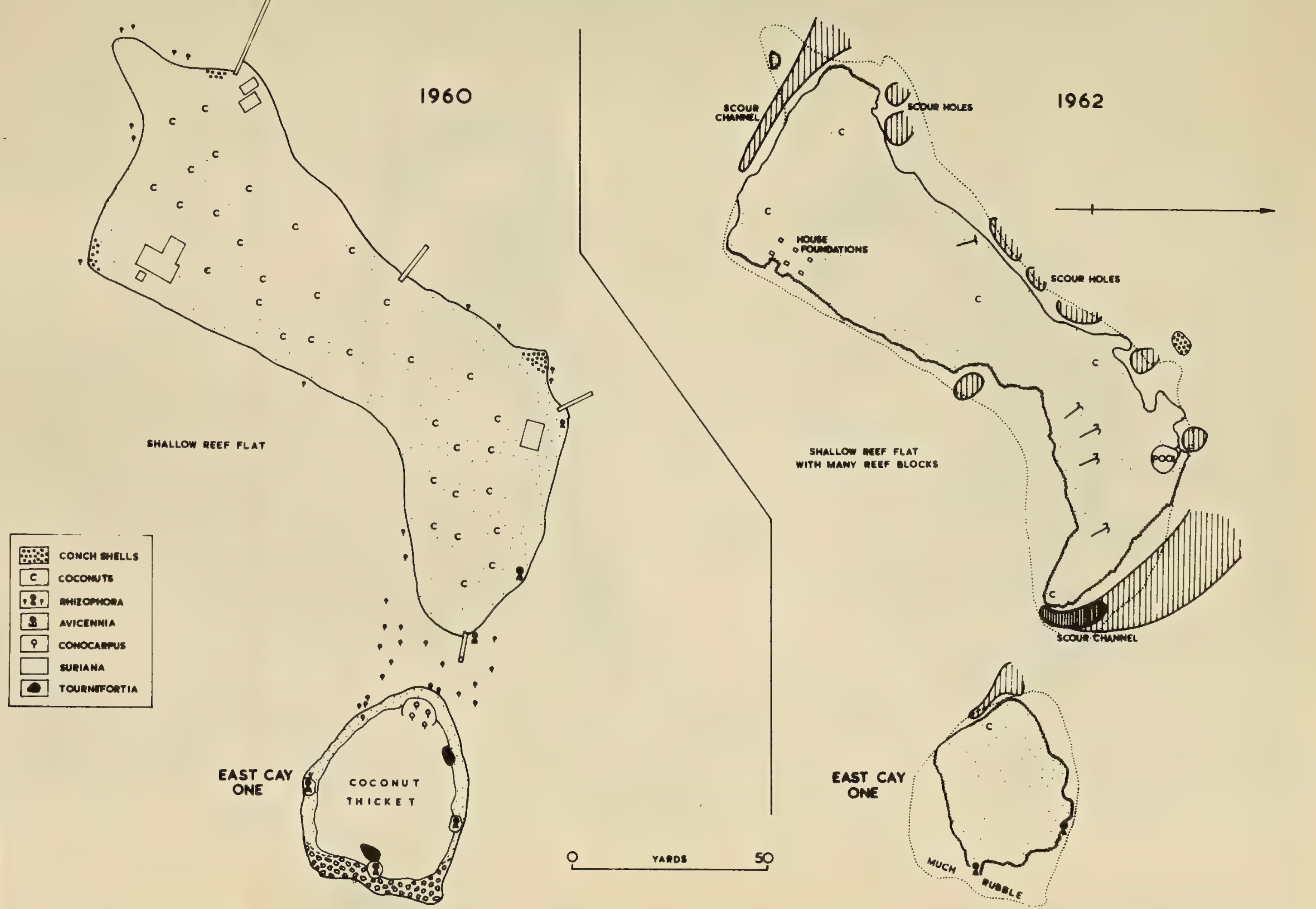


FIG. 48

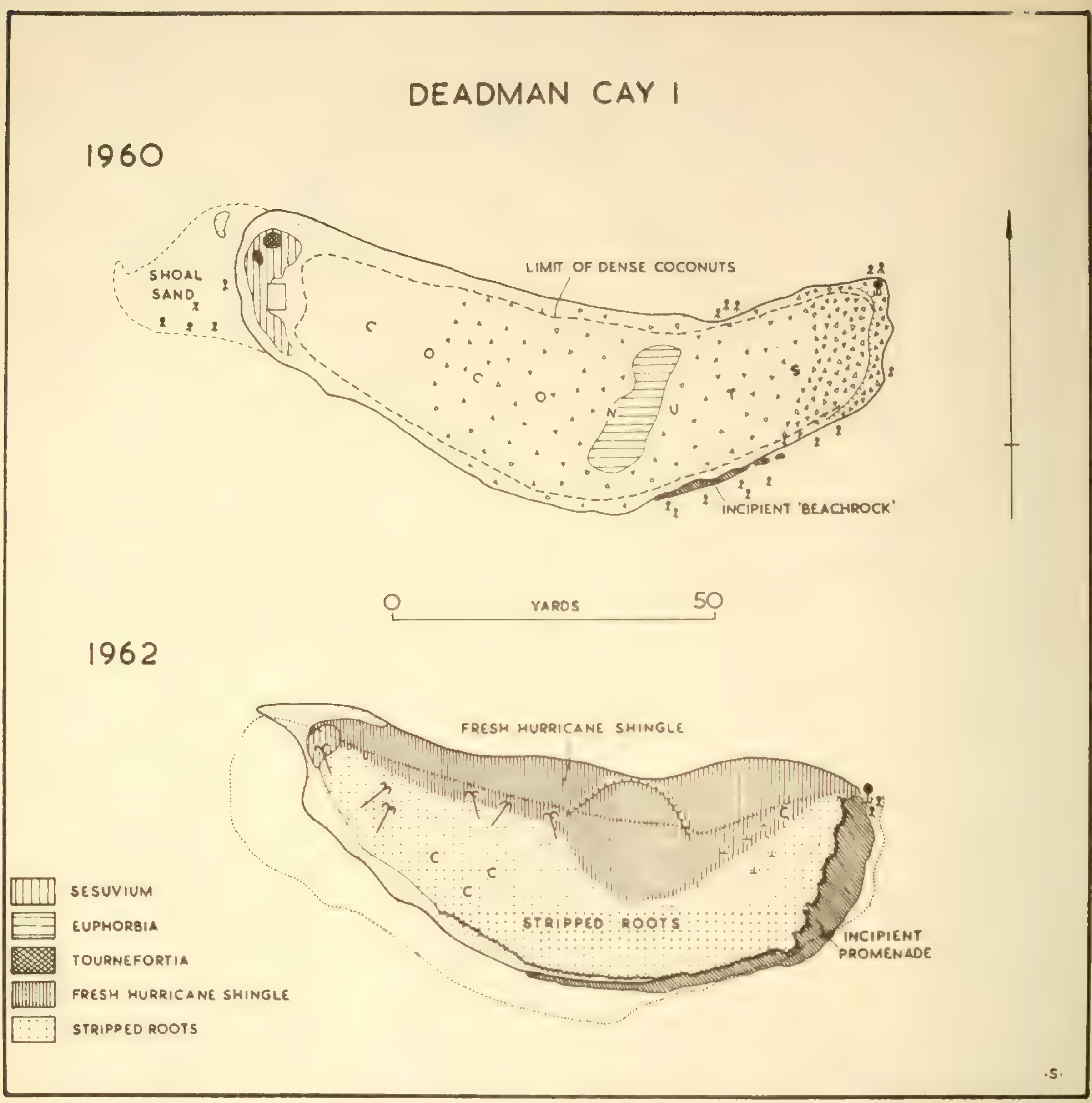

DEADMAN CAY I
1960
SHOAL SAND
LIMIT OF DENSE COCONUTS
C O C O N U T S
INCIPIENT 'BEACHROCK'
0 YARDS 50
1962
FRESH HURRICANE SHINGLE
STRIPPED ROOTS
INCIPIENT PROMENADE
SESUVIUM
EUPHORBIA
TOURNEFORTIA
FRESH HURRICANE SHINGLE
STRIPPED ROOTS
·S·

FIG 49

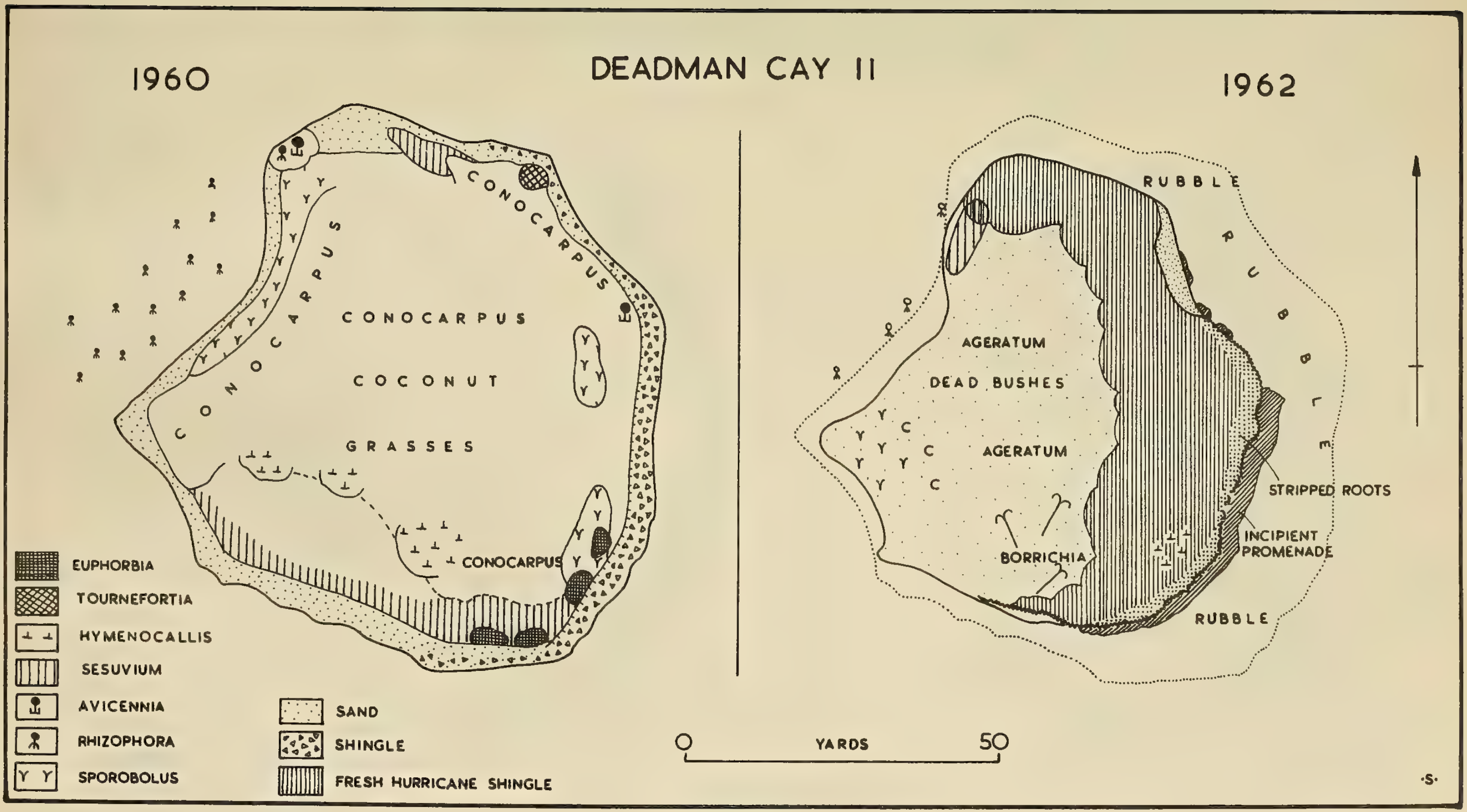

DEADMAN CAY II
1960
1962
CONOCARPUS
CONOCARPUS
CONOCARPUS
COCONUT
GRASSES
CONOCARPUS
CONOCARPUS
RUBBLE
RUBBLE
RUBBLE
AGERATUM
DEAD BUSHES
AGERATUM
BORRICHIA
STRIPPED ROOTS
INCIPIENT PROMENADE
EUPHORBIA
TOURNEFORTIA
HYMENOCALLIS
SESUVIUM
AVICENNIA
RHIZOPHORA
SPOROBOLUS
SAND
SHINGLE
FRESH HURRICANE SHINGLE
0 YARDS 50
·S·

FIG. 50

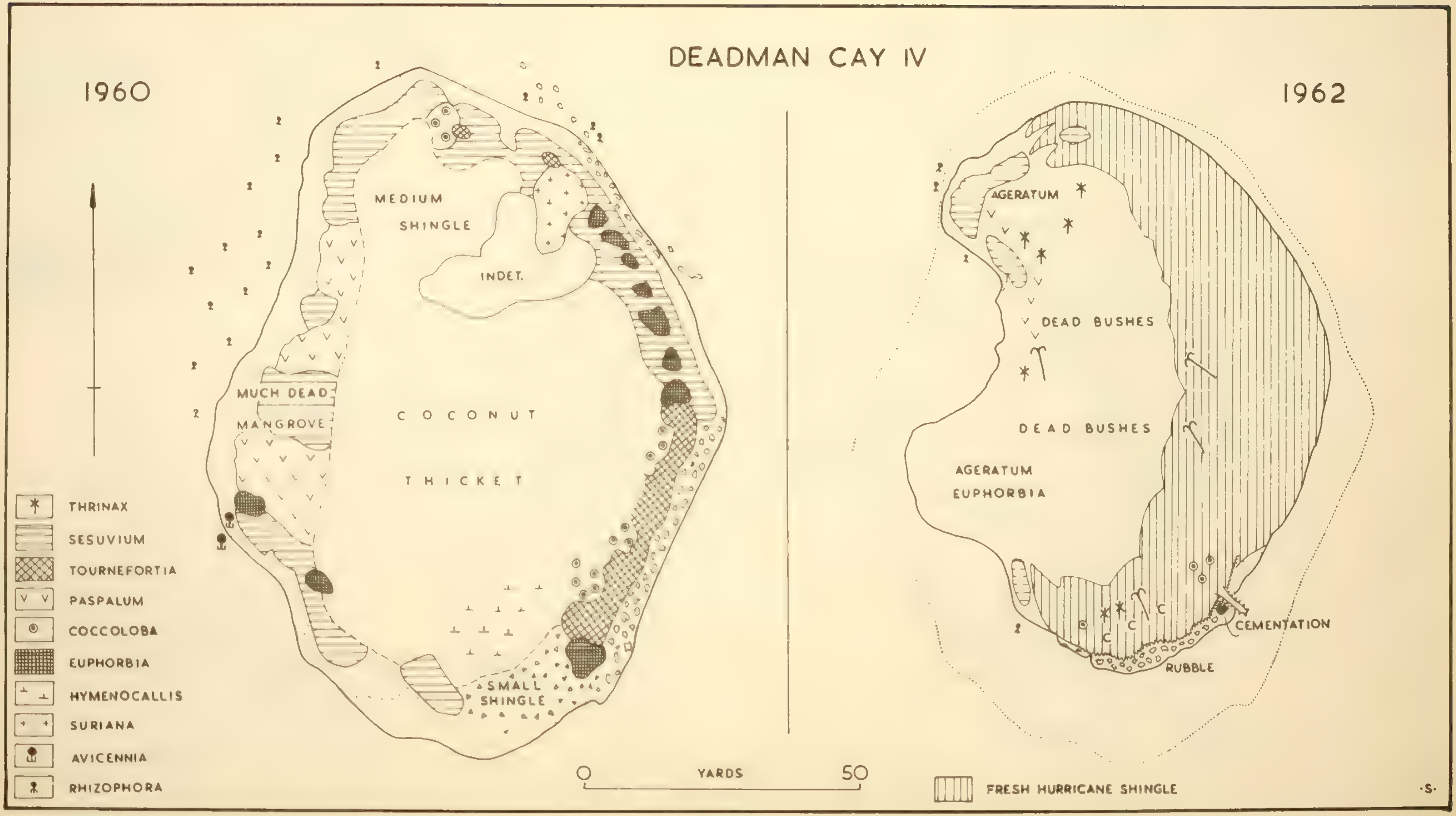

DEADMAN CAY IV
1960
1962
MEDIUM SHINGLE
INDET.
COCONUT
THICKET
MUCH DEAD
MANGROVE
SMALL SHINGLE
AGERATUM
DEAD BUSHES
DEAD BUSHES
AGERATUM
EUPHORBIA
CEMENTATION
RUBBLE
THRINAX
SESUVIUM
TOURNEFORTIA
PASPALUM
COCCOLOBA
EUPHORBIA
HYMENOCALLIS
SURIANA
AVICENNIA
RHIZOPHORA
0
YARDS
50
FRESH HURRICANE SHINGLE
·S·

FIG 51

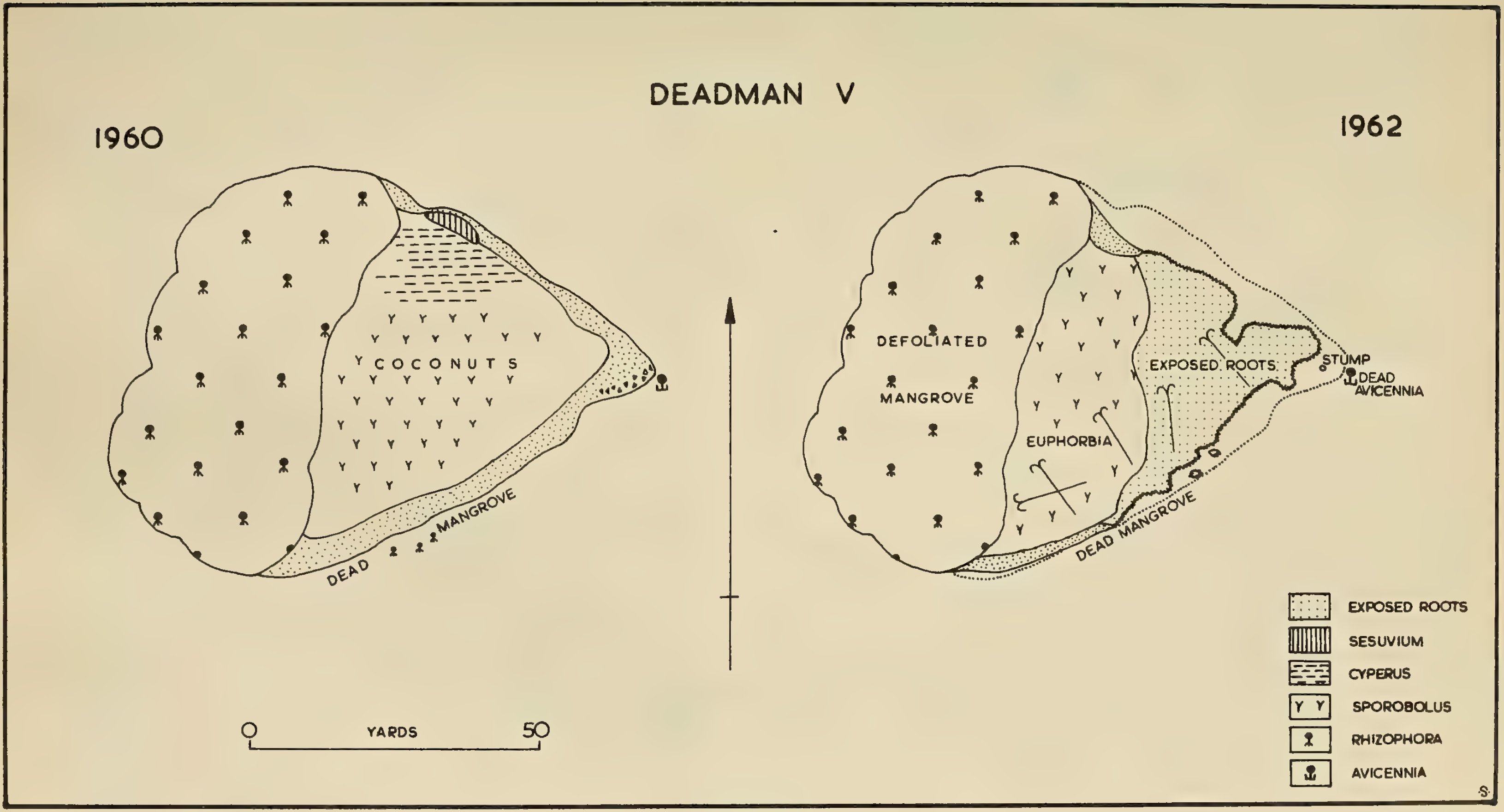
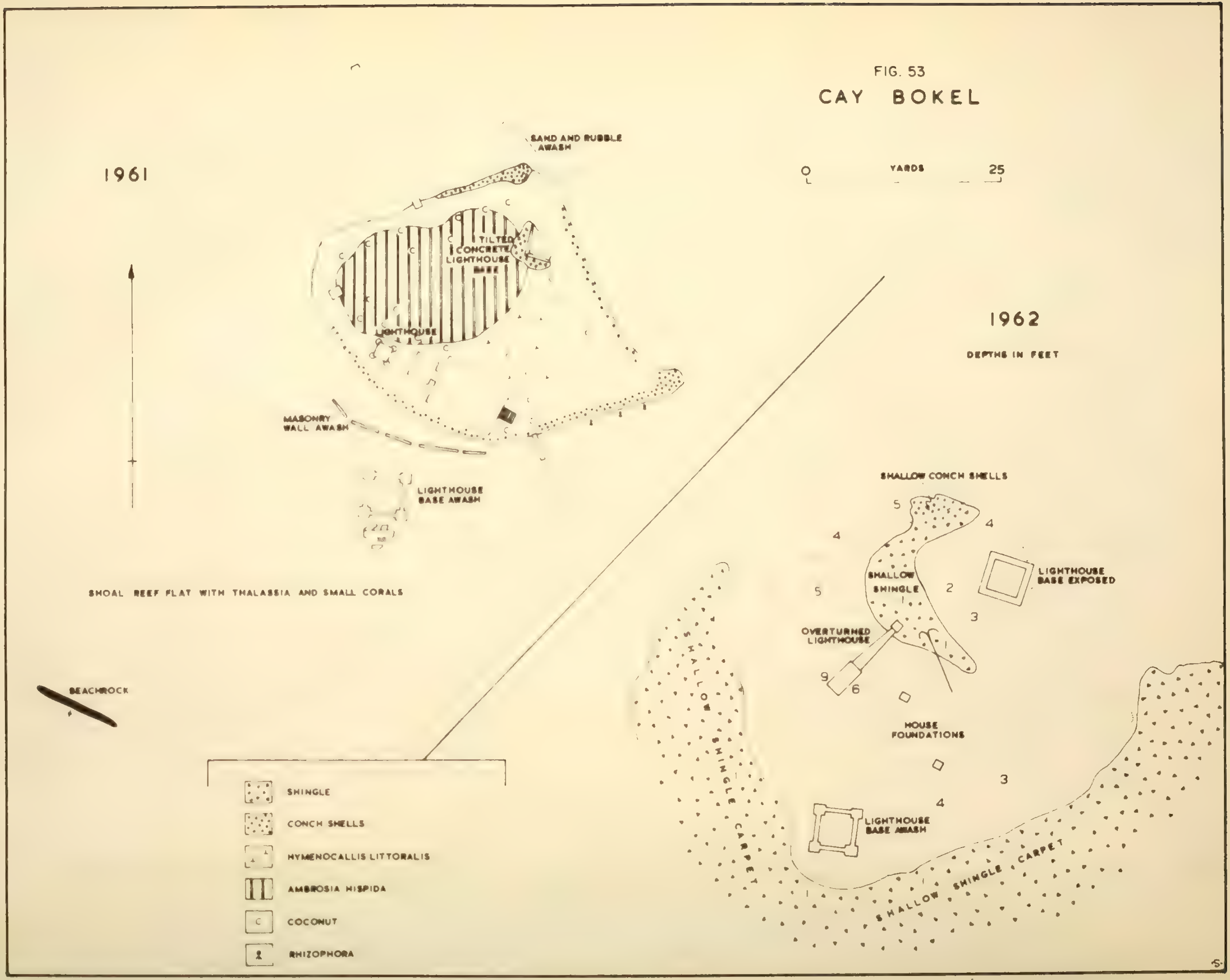

DEADMAN V
1960
1962
COCONUTS
DEAD MANGROVE
DEFOLIATED
MANGROVE
EUPHORBIA
EXPOSED ROOTS
STUMP
DEAD
AVICENNIA
DEAD MANGROVE
0
YARDS
50
EXPOSED ROOTS
SESUVIUM
CYPERUS
SPOROBOLUS
RHIZOPHORA
AVICENNIA

FIG. 52

FIG. 53

CAY BOKEL



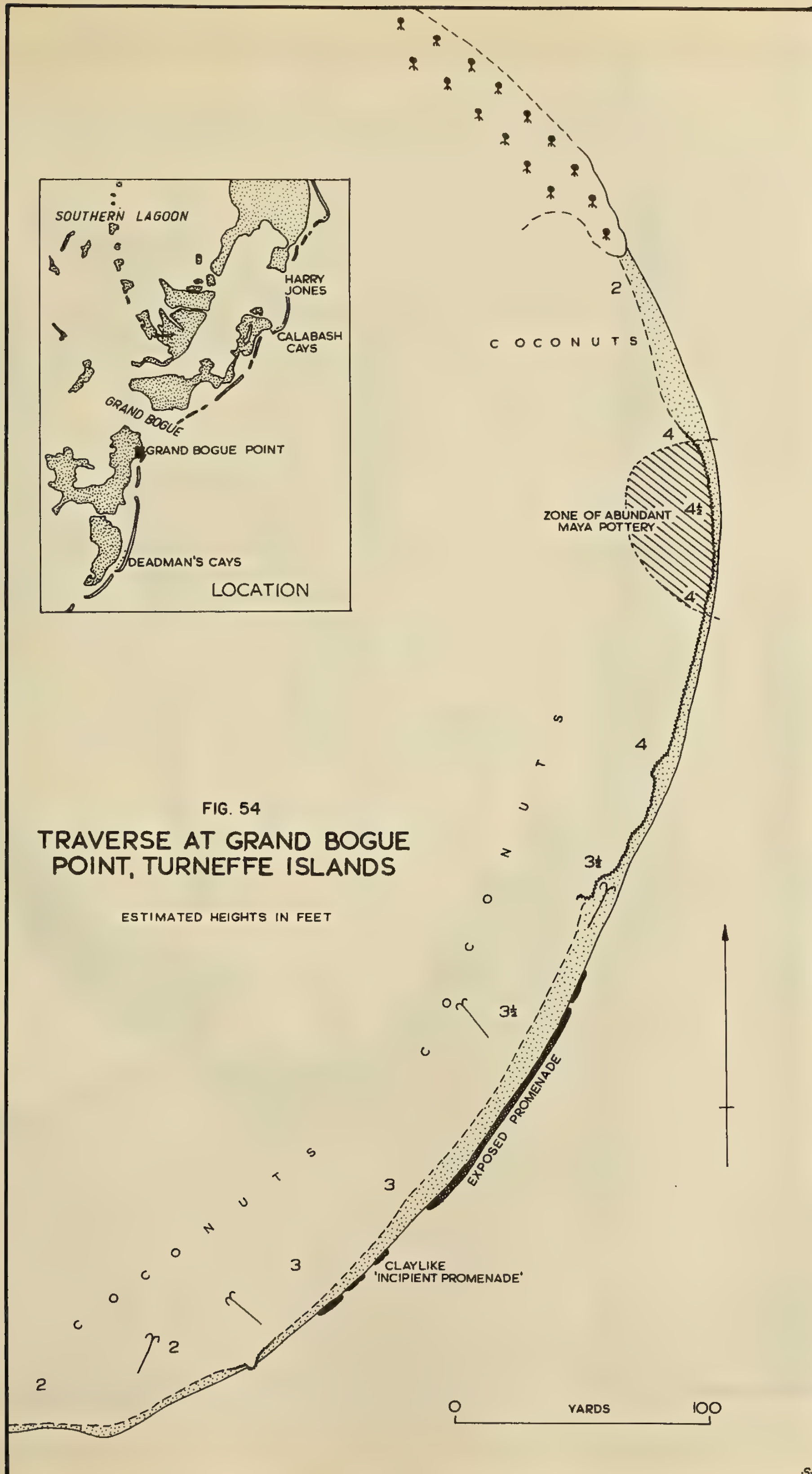


FIG. 54

TRAVERSE AT GRAND BOGUE POINT, TURNEFFE ISLANDS

ESTIMATED HEIGHTS IN FEET

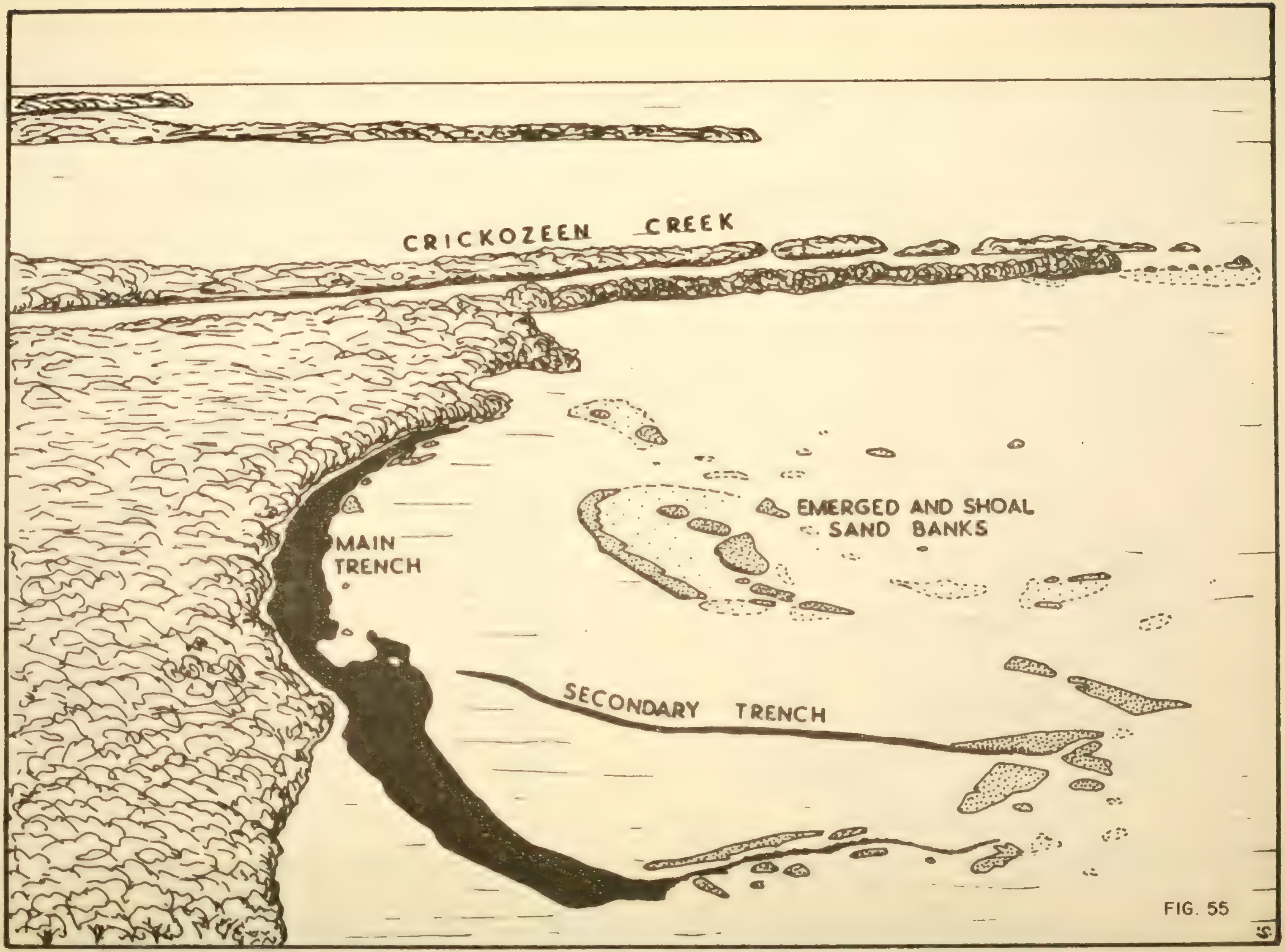


FIG. 55

AERIAL VIEW FROM NORTH OF CRICKOZEEN CREEK SLUMPING

DRAWN FROM A PHOTOGRAPH

VII. HURRICANE DAMAGE ON LIGHTHOUSE REEF

Lighthouse Reef, lying 11-18 miles seaward from Turneffe Islands, is the smallest of the three British Honduras atolls in area: it is 25 miles long, but has a maximum width of only $4\frac{1}{2}$ miles. The atoll is surrounded by a well-developed reef-rim, with only three major gaps, one at the north end, the others near the south end. The whole of the eastern reef north of Half Moon Cay is unbroken and backed by a wide reef flat; coral growth on the windward side is much more vigorous than on the leeward reefs. The central lagoon is generally shallower on the west side and deepens eastwards, with average depths near the east reefs of 2-3 fathoms and maximum depths probably reaching $4\frac{1}{2}$-5 fathoms. The shoal and deeper areas of the lagoon are separated by a "Middle Reef", parallel to the peripheral reefs. For a fuller description of the atoll, see ARB 87, 51-81 and Figures 27-36. There are two cays at the north end of Lighthouse Reef, Northern Cay and Sandbore Cay, collectively known as Northern Two Cays. The former is a large mangrove island with a wide seaward sand rim; the latter a small sand cay. At the south end of the reef, Long Cay is comparable in size and physiography to Northern Cay; Half Moon Cay is a large sand and shingle island; and, before the storm, Hat and Saddle Cays were smaller bush-covered sandy cays. All these islands lay to the south of the hurricane track, though the storm passed over the northernmost tip of the atoll and Northern Two Cays. An in previous chapters the islands are here described from north to south.

Sandbore Cay

Sandbore Cay is the most northerly island on Lighthouse Reef (ARB 87, 56-58), situated at the northern end of the long unbroken east reef, about 1000 yards back from the reef edge. In 1961 (Figure 56) the cay consisted in outline of a "core" at its eastern end, with two long spits extending westwards, enclosing a lagoon 4-5 feet deep. The gross outline of the cay was triangular, with sides of 300-500 yards: the northern spit was composite and formed a block of land some 150 yards square, the southern spit was long and narrow, varying in width from 20-65 yards. The whole island was sandy and nowhere more than 3 feet above the sea. The greatest elevations were found along the northeast and southeast facing shores. Beachrock before the hurricane was exposed at two points: Beachrock I consisted of two, perhaps three subdued lines of rock, dipping north, about 40 yards long, off the east end of the cay; Beachrock II consisted of a single line of rock 50 yards long and 18 inches wide, with a slight seaward dip, just exposed at low tide and rather difficult to see, along the southeast shore.

The east end of the island had been largely cleared for coconuts, but there were large areas of ground vegetation along the southeast shore, and particularly on the surface of the two spits. The southern spit supported Suriana maritima, Tournefortia gnaphalodes, Conocarpus erectus, some Avicennia, and an undercarpet of Euphorbia, Ipomoea, tall grasses, and considerable areas of Ambrosia hispida. Along the north-east shore and on the northern spit Suriana and Tournefortia were again

found on the beach crest, and Suriana was also scattered over the spit surface. At the head of the lagoon there was a thicket of Suriana, Conocarpus and Coccoloba, tall grasses such as Andropogon glomeratus, low grasses such Sporobolus, and Ambrosia. The pre-hurricane distribution of vegetation is shown in ARB 87, Figure 28.

There was some evidence of erosion along the cay shores, shown by beachrock on the south shore, and undercutting and falling coconuts along the northeast shore. Both spits seemed to be expanding westwards, shown, in the case of the northern spit, by broad concentric ridges of fresh sand in the first stages of colonisation by plants. The main evidence of progressive movement to the west, however, was provided by the lighthouse, built on the cay itself in 1885. Since that time the east shore has retreated, until in 1961 the light stood 80 yards from the shore. A concrete walk connecting cay and light was built in 1945; in 1961 this ended 20 yards from the shore as a result of yet further shore retreat. A wooden causeway had been built to connect the 1961 shore with the 1945 concrete walk. The average rate of shore retreat 1885-1945 was 3 feet per year; 1945-1961, 4 feet per year. Beachrock I at the east end of the cay is clearly related to this retreat of the last half century.

In my previous Bulletin, it was suggested that if the cay continued to retreat westwards at this rate, the time would come when it would be pushed off the reef flat altogether, leaving the lighthouse as its only memorial. Hurricane Hattie, however, disrupted this simple scheme. The centre of the storm passed over this island: wave activity was sufficient to destroy the concrete walk to the lighthouse by the afternoon of 29 October, and as the storm passed shortly after midnight, 30-31 October, the lighthouse itself collapsed in a pile of rubble. Severe physiographic and vegetation damage was caused by wind and wave action as the cay surface was submerged to a depth of 8 feet during the storm surge. Physiographic changes will be outlined first. The main lineaments of the cay still exist, though shore retreat occurred at the east point, along the south shore, and at the western ends of both sandspits. Two channels were cut through the spits: one 65 yards wide through the neck of the northern spit, the other 50 yards wide through the middle of the southern spit at its narrowest point. The first channel had been refilled with fresh sand to approximately its pre-storm height by May 1962, though the new neck is wider than before, with an irregular inner edge, and it is devoid of vegetation. There is no information on the date when the refilling began; the channel immediately after the storm is said to have been 3 feet deep. The second gap, through the southern spit, is still open, and varies from 2-3 feet deep. Beach erosion has greatly increased the exposure of Beachrock II along the south shore: it can now be traced for 140 yards in a wide arc following the old shoreline. The rock is not topographically conspicuous, but shows a noticeable seaward dip, and is distinguished from the surrounding Thalassia by its lack of vegetation. A second line of beachrock, Beachrock III, has been revealed along the old lagoon shore of the spit; it is a massive rock, in five distinct, sometimes overlapping plates, just breaking surface and at least $2\frac{1}{2}$ feet thick; it has a marked lagoonward (northwest) dip. No trace of this beachrock was previously apparent; nor can it be seen along uneroded portions of the lagoon shore, which presumably it also underlies. There is no sign that this channel is about to fill up. Sand

from the gap has been deposited in the lagoon itself, forming a wide shoal area which splits the lagoon into two parts: (a) the inner lagoon is now virtually enclosed, the water in it is stagnant and odoriferous, and there are slimy reddish deposits round the shores; (b) the outer lagoon still has depths of 1-1½ fathoms, but the floor is littered with blocks of living coral, some only a few feet from the shore, which were not previously seen. Tongues of shoal sand, emerging as fresh sand spits, have also been built westwards from the ends of the spits. A further fresh sand peninsula has been thrown up at the east end of the cay, flanking an elongate scour hole several feet deep.

Surface erosion of loose sand and exposure of roots has been greatest along the southern side of the island. Almost all coconuts have been swept away from this section, together with the Suriana and Tournefortia bushes, though a few patches of Euphorbia and grasses remain. The surface is now littered with coarse coral fragments, strewn with long coconut roots from which all the fine material has been flushed, and most difficult to walk over. There are numerous small scour holes, mostly at the upturned bases of coconut trees. The deepest hole is found on the southeast side of the only building to survive, a concrete house: the scour hole extends under the house foundations, is filled with water, and is at least 17 feet deep. Had the undermining continued longer the house would certainly have collapsed. A few coconut stumps still stand at the east end of the cay, but otherwise all the surface sand and vegetation has been removed; roots are combed in a NW-SE direction. The house itself is no longer used; only the central concrete strong room remains, the roofs and all remaining wooden rooms have been broken from the construction.

Damage on the northern spit beyond the severed neck has been less severe. The thicket of Coccoloba and Conocarpus still stands at the head of the lagoon, with a number of coconut trees which retained their crowns. The peripheral Suriana and Tournefortia bushes were all swept away, and marginal erosion all round the shores destroyed areas of grasses, Euphorbia, Ambrosia etc. In the centre of the spit the vegetation cover still survives largely intact, though thinner and partly buried by fresh sand. The larger bushes such as Conocarpus, Tournefortia and Coccoloba were defoliated and now appear to be dead, but the ground cover of Sporobolus, Cyperus, Cakile, Euphorbia and Ambrosia is still recognisable. There is a very great increase in the amount of "burr-burr", Cenchrus, throughout the area, but Ipomoea is less widespread. Surface sand has been stripped and roots exposed only in small areas on the southwest shore. One point of interest is the occurrence in the channel-like depressions cut into the old surface round the margins of the northern spit, of surface incrustations of cemented sand, c-¼ inch thick, covering several square yards. This caliche-like deposit can be lifted up in plates up to a foot in diameter, but rapidly crumbles in the fingers. It may be a salt incrustation produced by high insolation after the flooding of the island by the storm surge. A few Tournefortia seedlings were seen colonising the fresh sand margins of the northern spit in May 1962.

Northern Cay

Northern Cay, the largest island on Lighthouse Reef, has maximum dimensions of 3300 and 3000 yards and an area of $2\frac{1}{4}$ sq. miles, of which one fifth is interior lagoon, one fifth is dry land, mainly under coconuts, and three-fifths is mangrove and swamp land (ARB 87, 58-62, Figure 29). The dry land area lies on the north and west sides of the cay, where the shore approaches to within 400-600 yards of the reef. The western shore, 2600 yards long, was before the hurricane slightly undercut, forming a cliff 3-8 feet high. At the base of the undercut cliff cemented sands outcrop intermittently for about 1500 yards: the base of the outer edge has a near-constant altitude of about 1 foot above low tide level. In 1961 the exposure was 6-9 inches thick, and varied in width from a few inches to 2 feet; the upper surface was either horizontal or dipped slightly seaward and was much pitted and eroded. Slabs broken from the main exposure lay on the beach at the beach angle. The rock itself was well consolidated on the surface, but rather friable a few inches from it. During the hurricane, this eastfacing shore was not severely affected by wave erosion, though the sand ridge overlying the cemented sand was pushed back several feet. In places the cemented platform is now up to 8 yards in width, and its upper surface rises to 2 feet above sea level. The outer edge, previously exposed, is, as before, much pitted and blackened, and more slabs have been broken off or fractured. The freshly exposed section has a relatively smooth upper surface; cementation in the newly exposed area is poor compared with the outer zone; and the recency of the consolidation is shown by the presence of coconut roots within the rock. At one point along the shore, the cemented platform is buried by the main beach ridge, behind which a temporary section has been opened by the uprooting of a large coconut tree and scouring of the hole by waves. The rock horizon can be seen all round the hole: the upper surface is thin, friable and easily broken, and the sand below is uncemented (Figure 63). These exposures show that the rock is not an intertidal beachrock, but that it is forming at its present elevation as a cay sandstone, comparable to that at Big Cay Bokel, Grand Bogue Point, and Harry Jones, Turneffe. For a photograph of this sandstone before the hurricane, see Stoddart, 1962a, opposite p. 160.

The main shoreline changes at Northern Cay have taken place along the north shores, between the northern limit of this sandstone and the North Point; the changes are shown in detail in Figure 57. North Point, previously consisting of dune sands fixed by vegetation, mainly Euphorbia, Ambrosia, grasses and a few Conocarpus bushes, with ridge crests rising to 4 feet above sea level, has been swept away. A triangular area of sand 80 yards long, with a base of 160 yards, area 6400 sq. yards, has disappeared, though its former location is revealed by an area of shoal sand 2-3 feet deep, surrounded by Thalassia. The shoreline at the base of the peninsula now consists of a steeply undercut clifflet of roots. The shoreline of the northern bay, west of the Point, has retreated an average of 10 yards: actual erosion has, however, been greater than this. The old shore, now revealed by an eroded cliff of grey sand, has retreated 25-40 yards; in front of the cliff a fresh sand ridge has been banked. This ridge is up to 30 yards wide and 2 feet high, with much Thalassia, shells and echinoid remains. The coarseness and unsorted nature of the constituent material show that the greater part of the ridge is a hurricane construction, perhaps slightly altered and augmented

by post-hurricane wave action. Shoreline retreat has been greater on the east (northwest-facing) side of the bay, than on the west (northeast-facing) side. As a result of this retreat, the incipient beachrock seen in a small embayment in 1960 has been destroyed, and the nearshore vegetation of Suriana, Tournefortia and grasses has disappeared. Wave action was sufficiently great 30 yards from the shore and 6 feet above sea level to completely destroy and sweep away a large house, water tank and outbuildings on the northwest side of the cay.

On the eastern shore, damage is largely restricted to the north end. The jetty and small huts have been washed away, and much shoal sand deposited along the northern offshore area. Waves also destroyed pre-existing vegetation and smothered the surface with fresh sand over a zone 10-30 yards wide at this northern end. Elsewhere, damage has been slight. Beachrocks III and IV remain intact.

Away from the shores, physiographic change is negligible, even in the exposed higher dune area back of North Point where ridges rise up to 10 feet above sea level. In spite of inundation by the storm surge, at least of the marginal areas, deposition has been very slight. Some pock-marking of the surface has resulted from uprooting of coconuts, but apart from this, change in the interior has been almost wholly vegetational. Before the hurricane the dry sand areas were covered with coconuts, yielding up to 20,000 nuts a month a few years ago; recently, however, ground vegetation had been allowed to invade the coconut areas, making them almost impenetrable in places. The taller ground vegetation has been almost completely swept away by the storm, and access is now easy at all points. Ground vegetation now consists only of grasses, Cyperus, Euphorbia, Cakile, some Hymenocallis, with greatly increased amounts of Cenchrus (burr-burr). Probably 80% of the coconuts have fallen, though large numbers are still standing, with and without crowns, on the west side of the northern bay and along the eastern side of the island. It is said that these standing trees are unlikely to bear again. Direction of tree fall is extremely regular, varying from 100-130°, the majority lying 115-120°; there is a definite minority of trunks, less than 5%, which have fallen in the opposite direction, 320-340°. Since Northern Cay was in the direct track of the hurricane, it is possible that the main period of tree fall occurred between 2200 h, 30 October, and the passage of the eye at 0100 h, 31 October, in response to violent northwest winds immediately preceding the storm centre, and that some of those which survived succumbed to the equally violent south and southeast winds which immediately followed the eye in the early hours of 31 October. Only at the extreme southwest corner of the cay are tree-fall directions at all confused. Recovery of defoliated Rhizophora was beginning in May 1962 on the east shore of the cay; but mangrove at the southwest point seemed quite dead.

The island is no longer inhabited, and it seems unlikely that capital for clearing and replanting coconuts will be immediately forthcoming. It will be useful to observe the development of vegetation on the cay if human interference is kept to a minimum. It is possible, however, t that a lighthouse to replace that at Sandbore Cay may be erected near North Point. This would be safer during hurricanes, but the cay lacks the excellent small boat harbour of Sandbore Cay and its shores are

extremely exposed, especially during northers. It is in addition infested by biting flies, which made life difficult even on Sandbore Cay whenever they reached it; on such occasions all persons on the smaller cay used to sleep at the top of the light in order to escape them.

Saddle Cay

Saddle Cay, in 1960-61 a small island $2\frac{3}{4}$ miles north of Half Moon Cay on the inner edge of the main east reef flat, has had a long history of hurricane damage (ARB 87, 62-64). Before 1931 it was some 50 yards long; it was reduced to half this length in the hurricane of that year, and by half again in 1942. Other hurricanes progressively destroyed the sand area and hindered fresh accumulation until in 1960 only a clump of trees covering a land area 10 yards in diameter remained. The cay supported a thicket of _Rhizophora_, _Avicennia_, _Conocarpus_, and a couple of coconuts, with a ground cover of _Sesuvium_; it was used as a nesting place by ospreys. In my previous Bulletin I suggested that "a large hurricane passing over the cay now would probably destroy it altogether" (ARB 87, 63). Hurricane Hattie did. Saddle Cay has completely disappeared as a surface feature, though from the air one can still see the arcuate sand shoal on which it stood. The shoal after the hurricane carried 2-3 feet of water.

Half Moon Cay

Half Moon Cay has been described and mapped in some detail (ARB 87, 64-77, Figures 30-34), and an effort was made in 1962 to study hurricane damage in similar detail. Lines of levels were again surveyed across the cay and a fresh contour map prepared (Figure 58); this was then superimposed on the 1961 contour map (Figure 30) and a new map prepared (Figure 59), showing by isopleths the positive or negative change in altitude at any point, especially on the south and southeast shores of the cay. Lines of levels were surveyed across the island in 1962 in the same places as in 1961 to aid comparison. Sediment samples taken in 1961 are in the process of analysis; samples taken at the same locations in 1962 had not arrived in Cambridge when this account was written. This is, therefore, a preliminary account, and it is hoped to deal with sediment changes and distribution on Half Moon Cay in a later paper. Figure 60, showing changes in sediment composition, like the pre-hurricane map, ARB 87, Figure 31, is not based on the sediment samples but on field notes made during traverses, and is also preliminary. Finally, Figure 61 shows in outline the vegetation changes due to Hurricane Hattie; for the pre-hurricane picture, see ARB 87, Figures 33 and 34.

To a large extent these maps speak for themselves, and most of the important changes can be seen from them. The main features of the cay in 1961 (ARB 87, Figure 30) were (1) a storm ridge along the southeast shore of the tapering east end of the cay, the crest everywhere more than 7 feet above sea level, much of it more than 8 feet, and one small area near the northernmost part of the cay, 120 yards west of the lighthouse, reaching more than 10 feet above sea level. The ridge was built of sand with patches of small shingle at its foot; at its base there outcropped an extensive platform of beachrock, and accumulations of blocks torn from this platform were found along the base of the ridge and in places

on both the seaward and back slopes of the ridge. (2) The southwest shingle ridge, decreasing steadily in height from 9 feet at the south point to only 3 feet at its western end, with the calibre of the constituent shingle decreasing in the same direction, and covered with a thick hedge of Cordia sebestena. This section too, is fringed at and a little above mean sea level for much of its length by a conglomerate platform. (3) The cay surface to the north of these two ridges. On the eastern, tapering end of the cay, cleared for coconuts, the ridge proper is narrow and much of the back slope lies less than 4 feet above the sea. Along the western half of the island, covered with a dense thicket of Cordia, Bursera, Ficus and Neea woodland, the ground surface is generally more than 3 feet and much of it 4-5 feet above sea level. Near the junction between these two zones is an area in the centre of the cay of subsurface cementation, possibly phosphatic, covered with raw humus, and in 1960 under thick Ficus bush.

When remapped in 1962 the following physiographic changes were apparent: Eastern Section. The easternmost 85 yards of the cay, previously forming a steep shingle peninsula rising 6 feet above sea level, has been levelled by wave action to form a low shingle and sand spread 1-2 feet high. The cay proper now ends in a steep cliff forming a perfect cross-section of the island. Between this cliff and the lighthouse a number of scour channels have eaten back into the surface from the north shore of the cay; these are up to 5 yards long, and 3 feet deep at their inner ends; they are apparently the work of waves crossing the cay from south to north.

The crestline of the main east ridge has been pushed northwards; since the present crest now lies on the old back slope of the ridge, the effect has been to lower the maximum height of the crestline. Previously the greatest elevations lay 12-30 yards from the southeast shore; in 1962 the crestline lay 30 yards from the shore along most of its length. The general level of the ridge crest is now 6 feet; near the lighthouse it rises to 8 feet, and near the middle of the cay to 9 feet. Landward retreat of the crest has resulted in vertical lowering of the surface of at least 3 feet along the greater part of the seaward face of the ridge; over a distance of about 230 yards the vertical lowering has been at least 5 feet, and in one place 7 feet. This to some extent exaggerates the true amount of erosion, which is partially at least a landward shift; nevertheless the crestline is now lower for its whole length by approximately 2 feet and this lowering is not wholly balanced by deposition. Fresh sand has been thinly spread over the backslope of the ridge in arcuate pattern, but only at two points is the measured increase in height at all considerable; in both cases the increase is generally little more than a foot, with a maximum in one small area of 4 feet. Much of the area immediately back of the present crest has had surface sand stripped and coconut roots exposed, and the crest itself is often steeply undercut on the seaward side, in one place forming a vertical sand cliff 4 feet high.

There has been no major change in sediment distribution. The former high shingle ridges at the east point have disappeared, though on the north shore a remnant of the old ridge is now perched high on the cay surface. Fresh shingle is scattered along the ridge foot, and the older accumulations of conglomerate slabs have been shifted and augmented.

Coral blocks and conglomerate slabs are thinly scattered across the backslope of the ridge.

Western Section. The western section of the cay differs from the eastern part in that, first, its south shore faced the main hurricane winds, and second, it was densely vegetated. The old regular decrease in crestline height and shingle calibre from east to west, away from the eastern reefs, has been completely destroyed. In place of the gentle decrease in height from 9 feet to 3 feet east to west, the ridge now rises to a maximum of over 10 feet near the centre, and for about three-fifths of its length the crestline now stands more than 8 feet above the sea. The crest has also been pushed landward: before the hurricane it stood an average of 25 yards from the shore, in 1962 this had increased to 50 yards. Comparison of the two contour maps, therefore (Figure 59), shows an outer zone of net vertical loss, of the order of 1-3 feet, and an inner zone of net vertical gain of at least 1 foot, with an area near the centre of at least 5 feet. The calibre of the material varies. The sorting of sediments normal to the beach has also been destroyed. At present there is an accumulation of coarse shingle and coral blocks at the foot of the ridge; the greater part of the seaward slope is now coarse sand, in contrast to the dominant shingle of the pre-hurricane ridge; and there is a jumble of coral blocks and large debris in the broken bushes at the ridge crest. In places waves overtopping the newly deposited sediments at the ridge crest during the hurricane have scoured out plunge holes up to 2 feet deep in the old cay surface beyond, thus accentuating the sharp break of slope at the inner limit of hurricane deposition. At one place on the seaward slope, cemented rubble has been exposed, comparable to that found in the cay interior in 1961 and recalling the Cockroach II exposure on Turneffe Islands (Chapter 6). There has been some low-level aggradation at the extreme west end of the cay, a fine-shingle ridge enclosing two small pools.

The topographic balance of the cay has therefore been reversed by Hurricane Hattie. Previously the greatest heights, up to 10 feet, were found along the southeast shore; now similar heights are only found on the south shore. The width of the zone affected by the hurricane is very much less in the western section, covered with vegetation, than in the eastern part, cleared for coconuts, and it is clear that the increase in height in the former is largely the result of piling-up of material against the dense vegetation hedge. It is very probable that considerable physiographic damage would have been caused at the west end, had that part of the cay also been cleared for coconuts. Over the greater part of the cay surface, especially at the west end, there has been no topographic change. Erosion along the northern shores has also been slight. At one point, 95 yards from the northwest point, shore retreat has exposed further cemented material similar to that in the middle of the cay. The top of its outer edge lies 2.8 feet above sea level, and its base 1.7 feet. The exposure is 9 feet wide, and rises very slightly inland; it is covered by shingle and dark sand, with the cay surface lying 4 feet above sea level. It is clearly not a raised beachrock, but formed at its present elevation beneath the cay surface, in the same way as the possibly phosphatic rock in the centre of the cay.

It should be noted that retreat of the ridge crest on the seaward side is beginning to expose the base of the lighthouse. This steel structure was built in 1931, on a much earlier brick foundation with the inscription "Completed December 1848. J. Grant, Builder". Several feet of sand were washed away from the base of the light during the hurricane and the bottom of the brickwork is now exposed, free of sand, on the seaward side. Further retreat will certainly endanger the light itself. In parenthesis here, reference may be made to a point made by Vermeer (1959, 9,12) that the original lighthouse was built in 1845 "midway between the north and south sides" of the cay, and that its present position directly overlooking the seaward shore indicates net migration of the cay northwards. This is probably an exaggeration; I have since discovered in the copy of the Honduras Almanack for 1832 which formerly belonged to Mrs. Matthew Newton, wife of the first incumbent of St. John's Cathedral, Belize, a lithograph of the 1820 lighthouse, quite clearly built on the crest itself. It may be compared with the De Mayne sketch, ARB 87, Figure 32. Old brickwork exposed by the 1961 hurricane adjacent to the present light could possibly be the base of the older light. It seems doubtful whether very great retreat has in fact taken place at this point since 1820; most of the shore retreat has taken place at the head of the bay, between the light and the south point, and at the south point itself.

Effect on vegetation

The discussion of effects on vegetation may conveniently be divided into effects on coconuts, the Cordia thicket, strand vegetation, and interior ground vegetation. At least 80% of the coconuts were felled by the storm (Figure 61); the only trees to escape were those near the lighthouse at the east end. Scattered individuals, some retaining their crowns, are found over the rest of the cay, but the general picture is one of innumerable aligned fallen trunks. Direction of fall varies from 30-45° at the east end to 50-75° over the rest of the cay. The majority of the trunks are oriented about 60°, clearly indicating winds a little west of southwest, which is in harmony with the pattern of shore-line change.

Damage was also severe to the Cordia-Bursera thicket. Its seaward margin was pushed landward by up to 25 yards, leaving a wide expanse of bare fresh sand, scattered in the east with isolated broken Cordia and in the west by broken Bursera. In contrast to the straight, extremely regular, pre-hurricane hedge, the seaward margin of the thicket is now extremely irregular, with deep indentations, which at one point almost cut the thicket into two parts. Cordia suffered worst damage, losing branches and trunks and often being wholly uprooted and piled on the ridge crest in great confusion. Nevertheless, even totally dead-looking specimens may still be alive; one much broken tree was seen which totally lacked leaves, but exhibited a solitary flower in April 1962; in such cases, of course, mortality may simply be delayed. Bursera suffered less damage, the trunks generally still standing in the position of growth, and retaining many branches, though losing all leaves and with many roots exposed. Even the inner regions of the thicket were damaged. Thus, in the region of subsurface cementation in the centre of the cay, previously

only reached by scrambling through a dense tangle of Ficus and other trees, all the larger plants were blown down. The thin surface humus has since been washed away and the rock is now exposed at the surface. Much of this vegetation rubbish has been cleared away and used for firewood. The main part of the thicket is much broken, and at a rough estimate the mean height has been reduced from 25-30 feet to less than 15 feet. The broken trunks and branches make it virtually impenetrable now.

Strand vegetation suffered more heavily still. All Suriana has been swept away, together with all Tournefortia, except for a single specimen at the east point. Plants such as Sporobolus and Hymenocallis in exposed situations have also disappeared. On the other hand, where thinly buried by fresh sand, Hymenocallis is reappearing, and the strand and fresh sand areas are being rapidly colonised by, for example, Cakile lanceolata, Sporobolus, burrburr (Cenchrus), and even a few seedlings of Tournefortia. Interior ground vegetation has been little affected. Large areas in the middle of the cay and to the north of the Cordia-Bursera thicket are still covered with grasses, Wedelia, Euphorbia, Ipomoea and Stachytarpheta, and bushes such as Rivina humilis, Ernodea littoralis and Conocarpus. Sporobolus, Cenchrus and Euphorbia mesembrianthemifolia are certainly extending on the previously cleared eastern half of the cay beneath the fallen coconuts.

Bird Colony

Half Moon Cay is noted for the colony of Red-footed Boobies, Sula sula sula, recently studied by Verner (1959, 1961) and Van Tets. Verner counted the number of birds in the colony as 3500 in 1958. There does not appear to have been any reduction in numbers as a result of Hurricane Hattie; the casual observer has the opposite impression, largely because of the breaking down of trees, stripping of foliage, and greater visibility of the birds. However, the nesting season may have been delayed. For some weeks after the hurricane the birds were described as wandering on the beaches rather than building nests. Cay inhabitants state that the boobies normally build their nests in November, lay in December, and hatch in January and February. Verner has shown that in 1958 the cycle was rather more prolonged than this: eggs were being laid from mid-November 1957 to mid-April 1958 (Verner, 1961, 584-585). After Hurricane Hattie (October 31), nest building did not begin until February, the birds laid in March, and the first hatched booby was seen on April 21. By contrast, in 1958 Verner saw flying young as early as April 1 (1961, 584). On May 10 1962, during a second visit, there were still very many unhatched eggs. The apparently obvious conclusion that nesting was delayed by the hurricane must, however, be accepted with caution; Verner has suggested that the cycle may be of more than 12 months duration and hence activities all start later every year (personal communication, 1962). Local fishermen all accepted that delay had in fact occurred.

Long Cay

Long Cay, the second largest island on Lighthouse Reef, is similar in build to Northern Cay (ARB 87, 77-81, Figure 35): it is a little more than 2 miles long, and varies in width from less than 300 yards in the

south to a maximum of 1200 yards in the north. Its total area is 525 acres, of which 8% is dry land and the rest mangrove swamp, bare mud and standing water. The main dry land area lies at the northwest corner, and has been cleared for coconuts; this section covers 22 acres. A further sand area extends for 1800 yards along the east side of the main mangrove area; it varies in width from 20-40 yards, is generally between 1 and 2 feet high, and is again planted to coconuts.

Physiographic damage to the northern sand area was slight, apart from shore retreat of up to 2 yards on the west and east shores. The north shore is protected by a belt of Rhizophora, which now seems quite dead. Shore retreat involved destruction of the jetties and also undermining and unroofing of a large new house on the northeast shore. On the low-lying east and northeast shores a thin new carpet of fresh sand has been deposited near the beach. On the higher west shore, retreat has involved cliffing, together with sand stripping and root exposure over a narrow zone immediately inland from the cliff. This is succeeded by an irregular zone of freshly deposited sand, through which the older vegetation protrudes. The total width of the erosion and deposition zone from the cliff edge varies up to 55 yards, but is generally 20-30 yards. Near the site of the old jetty on the west side there is a large stranded iron barge of unknown origin.

The most important vegetational effect has been the uprooting of coconuts, often leaving surface depressions filled with water. These holes are generally less than 3 feet deep, but may be 2-3 yards in diameter. Direction of tree fall is fairly constant, mainly 50-60°, but in places 25-30°. There is a widespread patchy vegetation between the fallen trees of Stachytarpheta jamaicensis, Euphorbia, Sesuvium portulacastrum, Cyperus planifolius, and grasses, together with a little Batis maritima and Borrichia arborescens. Perhaps 70% of the trees are down.

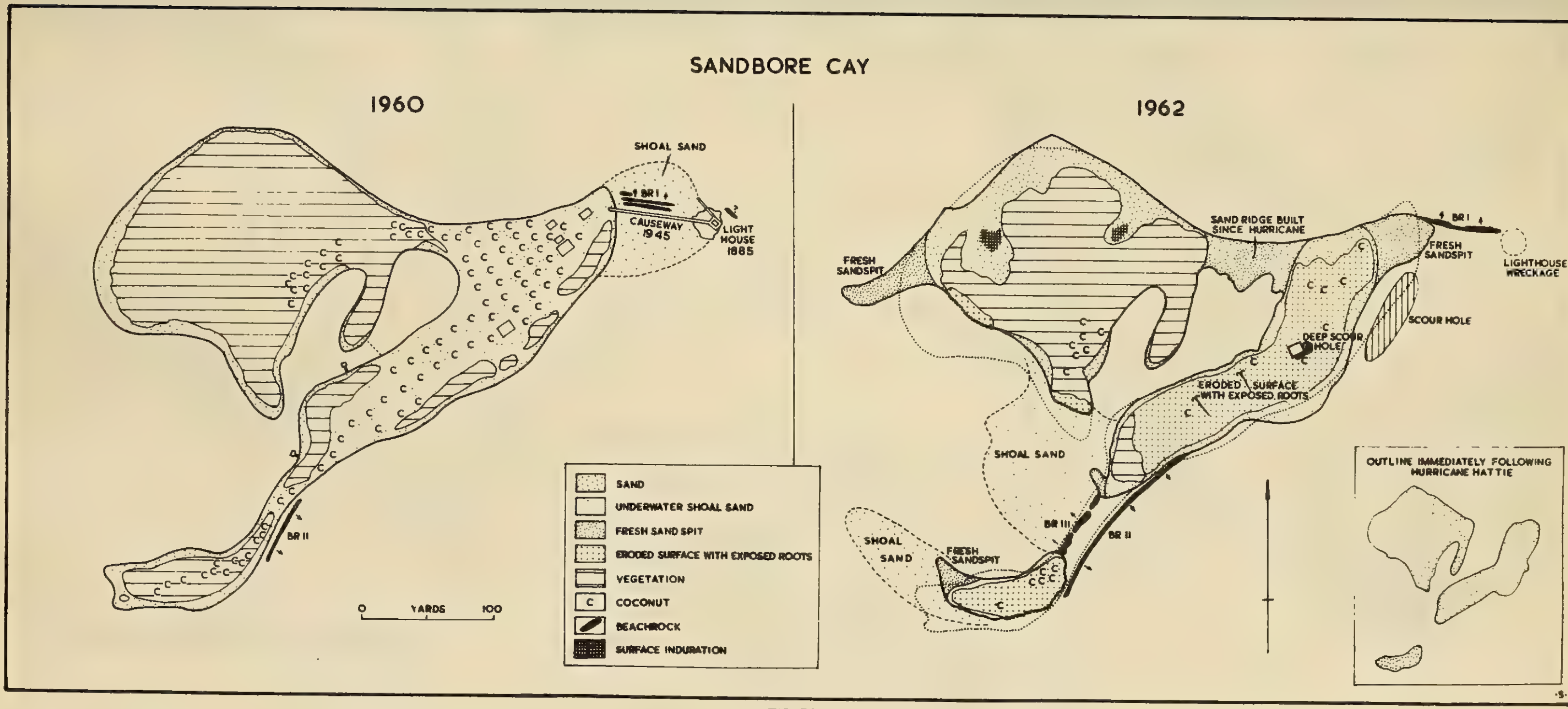
On the eastern sand ridge the picture is very similar. Shoreline retreat has been minor, but nearshore mangroves are all defoliated. Sophora and Suriana are no longer to be seen, but there is a fairly continuous cover of Borrichia arborescens, with Ernodea littoralis, Stemodia maritima, Euphorbia, Cyperus and grasses. Near the shore the direction of tree fall seems affected by wave action, varying from 340-010° near the mangrove edge, away from the shore, the direction is more constant at 60-70°.

The small amount of damage at Long Cay clearly results from the fact that winds were west and southwest at this point, and heaviest wave and wind action occurred along the mangrove coasts of the island. These were not mapped, and there is no means of telling in detail how they have changed; it is doubtful whether there has been any significant shoreline alteration.

Hat Cay

Hat Cay is the southernmost island on Lighthouse Reef, about 1¾ miles south of Long Cay. It is sandy, with maximum dimensions of 55 x 70 yards, and the surface does not rise more than 2 feet above sea level. Much of

the vegetation consisted of mangroves (Avicennia, Rhizophora, Conocarpus), with some Borrichia, Suriana, Sesuvium, Hymenocallis and Sporobolus (ARB 87, 81, Figure 36). The cay was not revisited after the hurricane, but was photographed from the air. The encircling mangrove still stands but is completely defoliated. Much of the interior vegetation has disappeared, exposing bare sand. There has not, however, been any significant change in the size or shape of the cay. This is rather surprising in view of its exposed situation and the dominance of southwesterly hurricane winds.



SANDBORE CAY
1960
SHOAL SAND
BR I
CAUSEWAY
1945
LIGHT
HOUSE
1885
BR II
0
YARDS
100
SAND
UNDERWATER SHOAL SAND
FRESH SAND SPIT
ERODED SURFACE WITH EXPOSED ROOTS
VEGETATION
COCONUT
BEACHROCK
SURFACE INDURATION
1962
FRESH
SANDSPIT
SAND RIDGE BUILT
SINCE HURRICANE
BR I
FRESH
SANDSPIT
LIGHTHOUSE
WRECKAGE
SCOUR HOLE
DEEP SCOUR
HOLE
ERODED SURFACE
WITH EXPOSED ROOTS
SHOAL SAND
BR III
BR II
SHOAL
SAND
FRESH
SANDSPIT
OUTLINE IMMEDIATELY FOLLOWING
HURRICANE HATTIE

FIG. 56

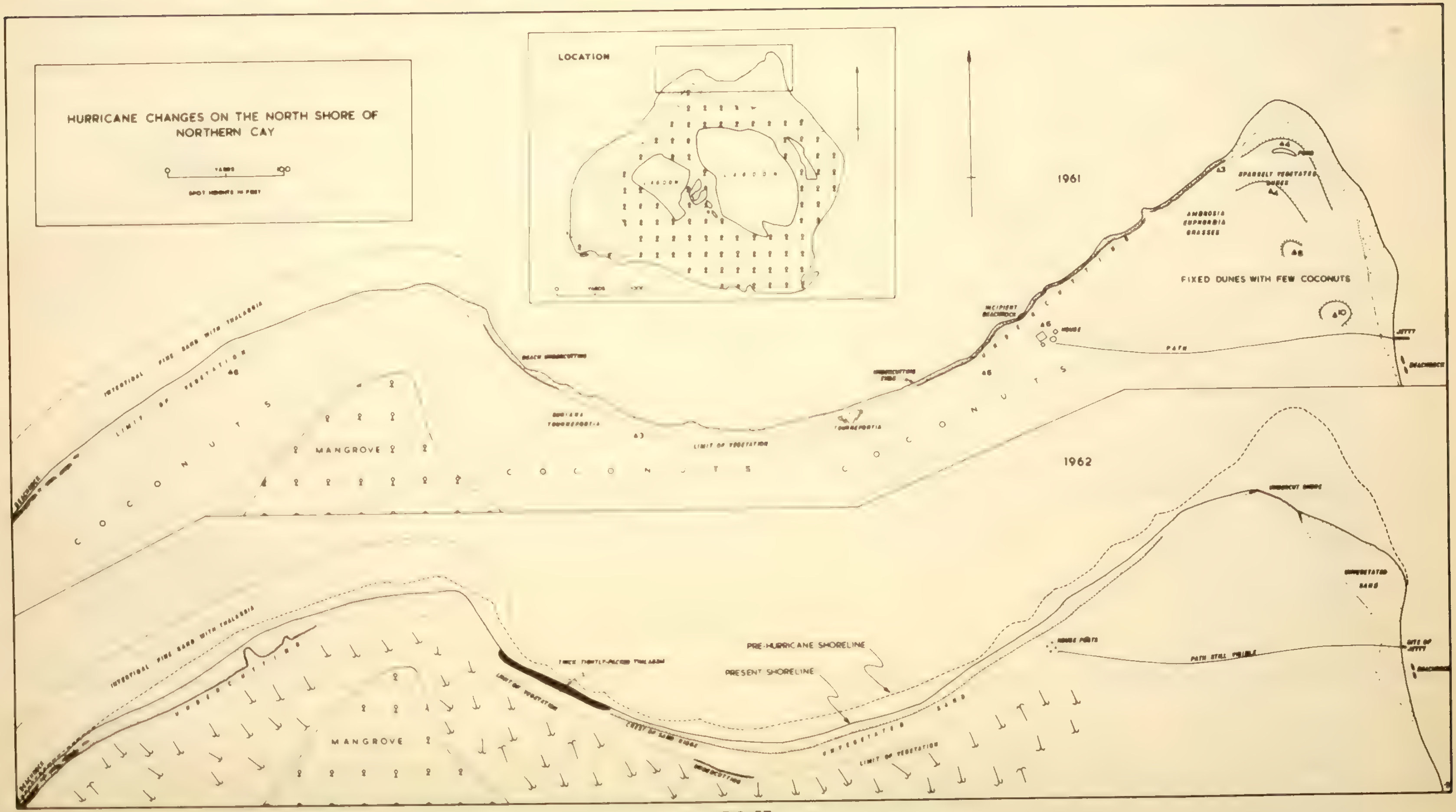

HURRICANE CHANGES ON THE NORTH SHORE OF NORTHERN CAY
SPOT HEIGHTS IN FEET
LOCATION
LAGOON
LAGOON
1961
1962
FIXED DUNES WITH FEW COCONUTS
AMBROSIA
EUPHORBIA
GRASSES
SPARSELY VEGETATED DUNES
POND
INCIPIENT BEACHROCK
HOUSE
PATH
JETTY
BEACHROCK
BEACH UNDERCUTTING
LIMIT OF VEGETATION
MANGROVE
COCONUTS
TOURNEFORTIA
INTERTIDAL FINE SAND WITH THALASSIA
UNDERCUT DUNES
UNVEGETATED SAND
HOUSE POSTS
PATH STILL VISIBLE
SITE OF JETTY
PRE-HURRICANE SHORELINE
PRESENT SHORELINE
CREST OF SAND RIDGE
UNDERCUTTING
UNVEGETATED SAND
MANGROVE

FIG 57

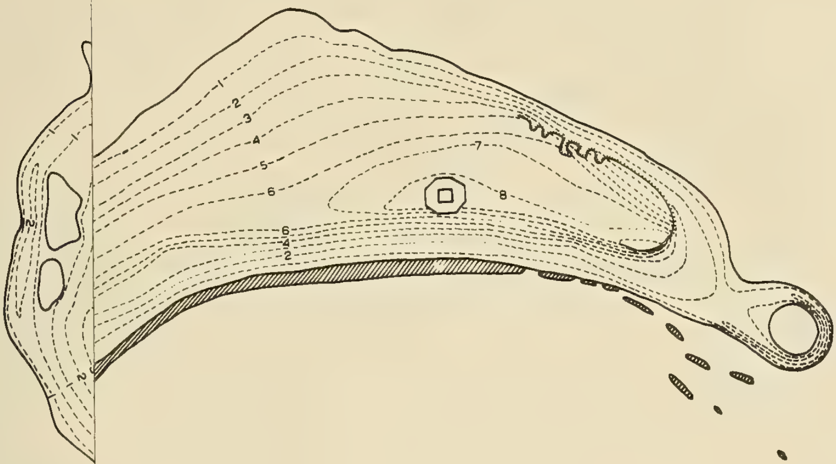


FIG. 58

HALF MOON CAY

TOPOGRAPHY IN 1962

CONTOUR INTERVAL
ONE FOOT

YARDS 200

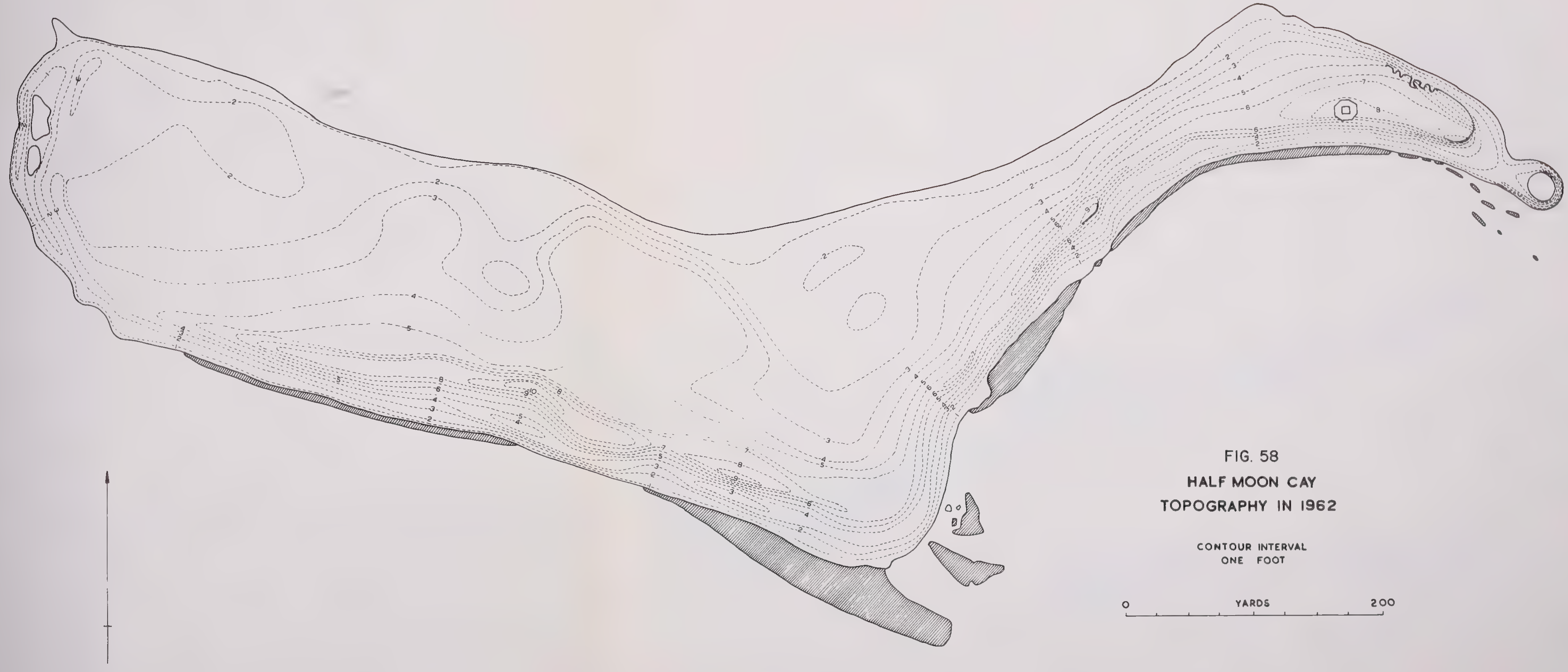


FIG. 58
HALF MOON CAY
TOPOGRAPHY IN 1962

CONTOUR INTERVAL
ONE FOOT

0 YARDS 200

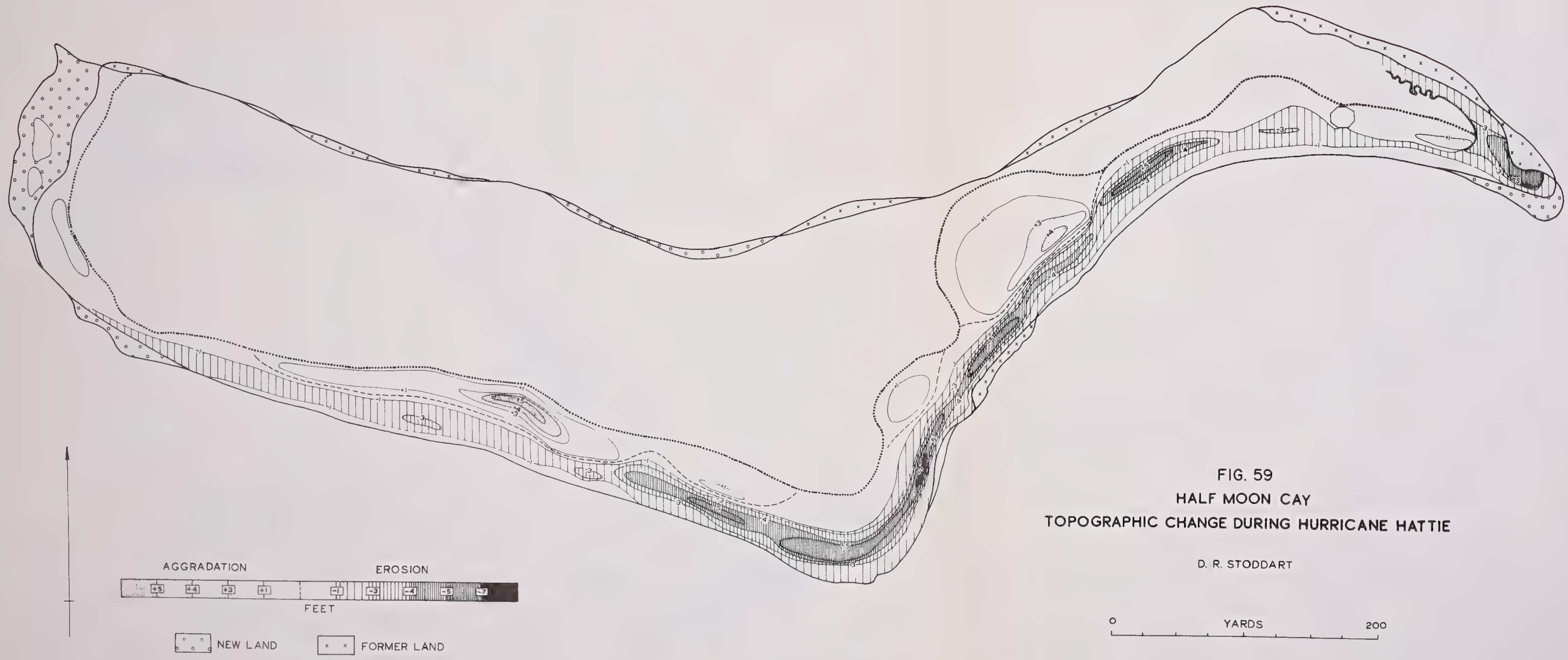


FIG. 59

HALF MOON CAY

TOPOGRAPHIC CHANGE DURING HURRICANE HATTIE

D. R. STODDART

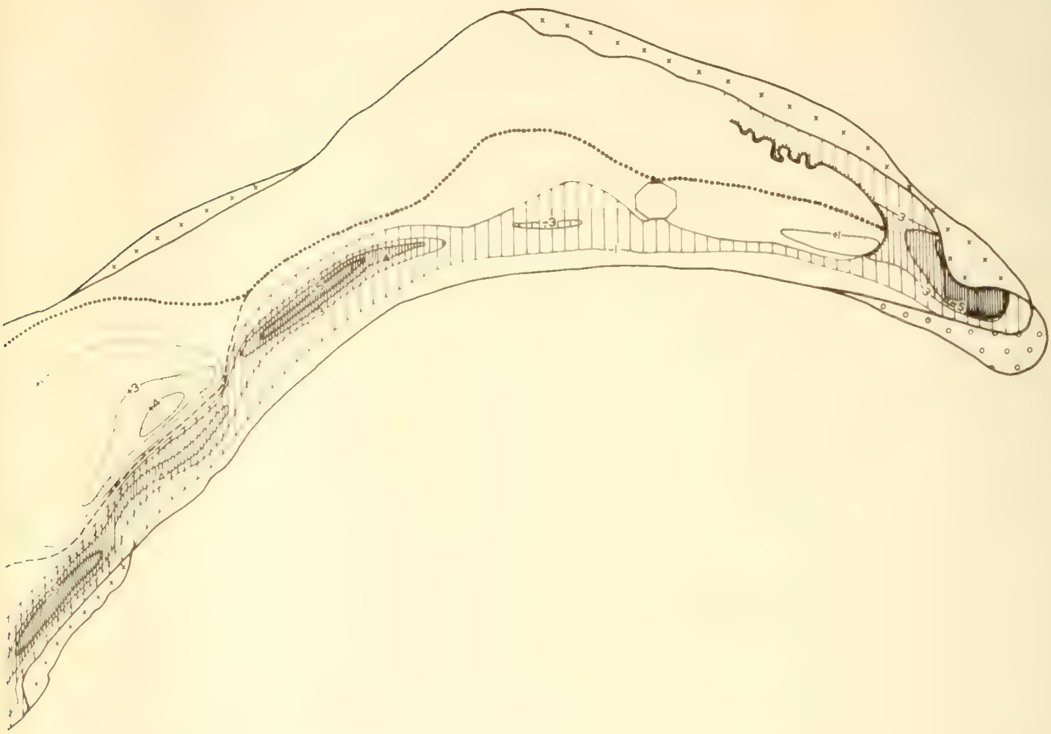


FIG. 59

HALF MOON CAY

TOPOGRAPHIC CHANGE DURING HURRICANE HATTIE

D. R. STODDART

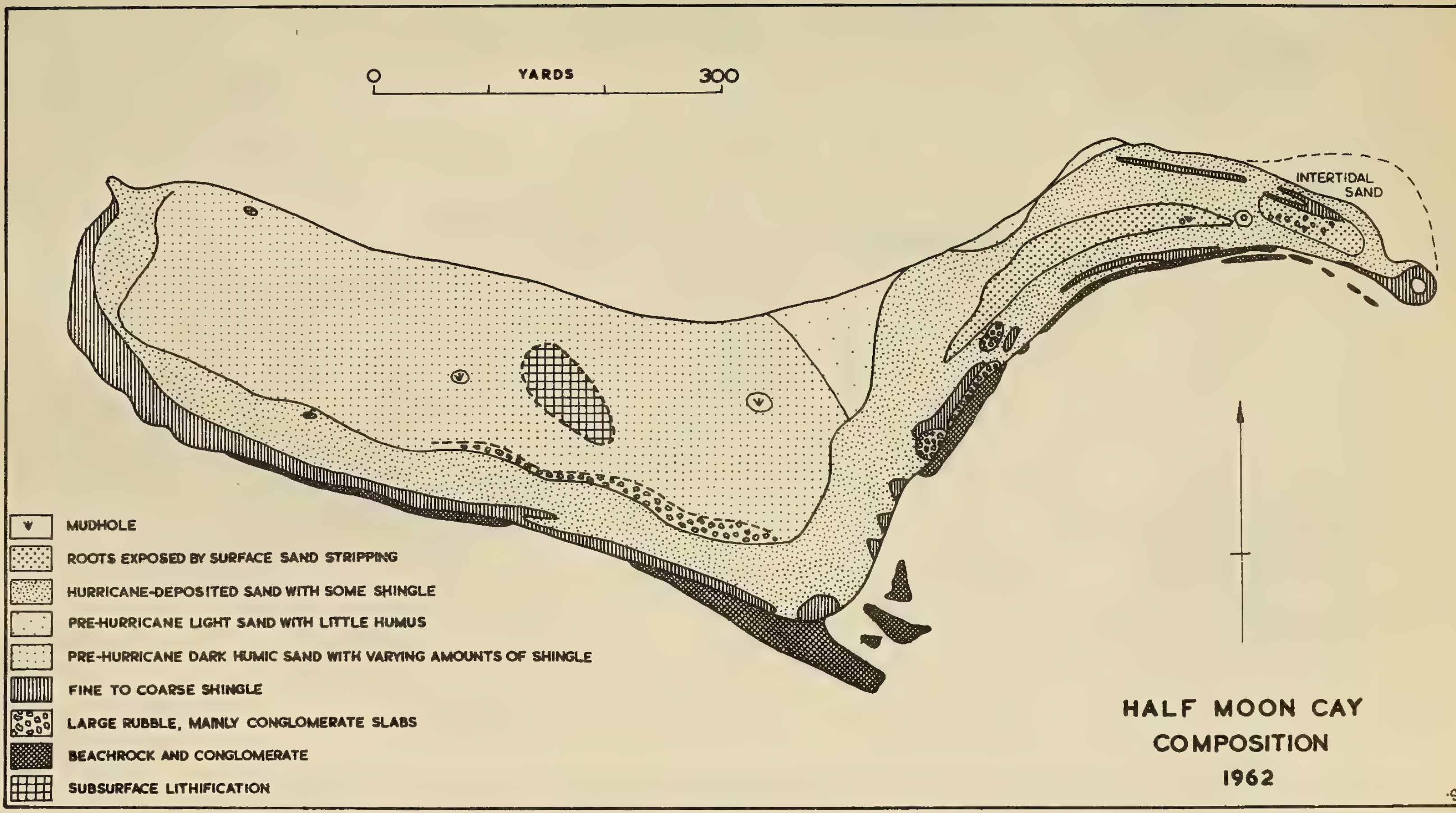

0
YARDS
300
INTERTIDAL SAND
MUDHOLE
ROOTS EXPOSED BY SURFACE SAND STRIPPING
HURRICANE-DEPOSITED SAND WITH SOME SHINGLE
PRE-HURRICANE LIGHT SAND WITH LITTLE HUMUS
PRE-HURRICANE DARK HUMIC SAND WITH VARYING AMOUNTS OF SHINGLE
FINE TO COARSE SHINGLE
LARGE RUBBLE, MAINLY CONGLOMERATE SLABS
BEACHROCK AND CONGLOMERATE
SUBSURFACE LITHIFICATION
HALF MOON CAY
COMPOSITION
1962

FIG. 60

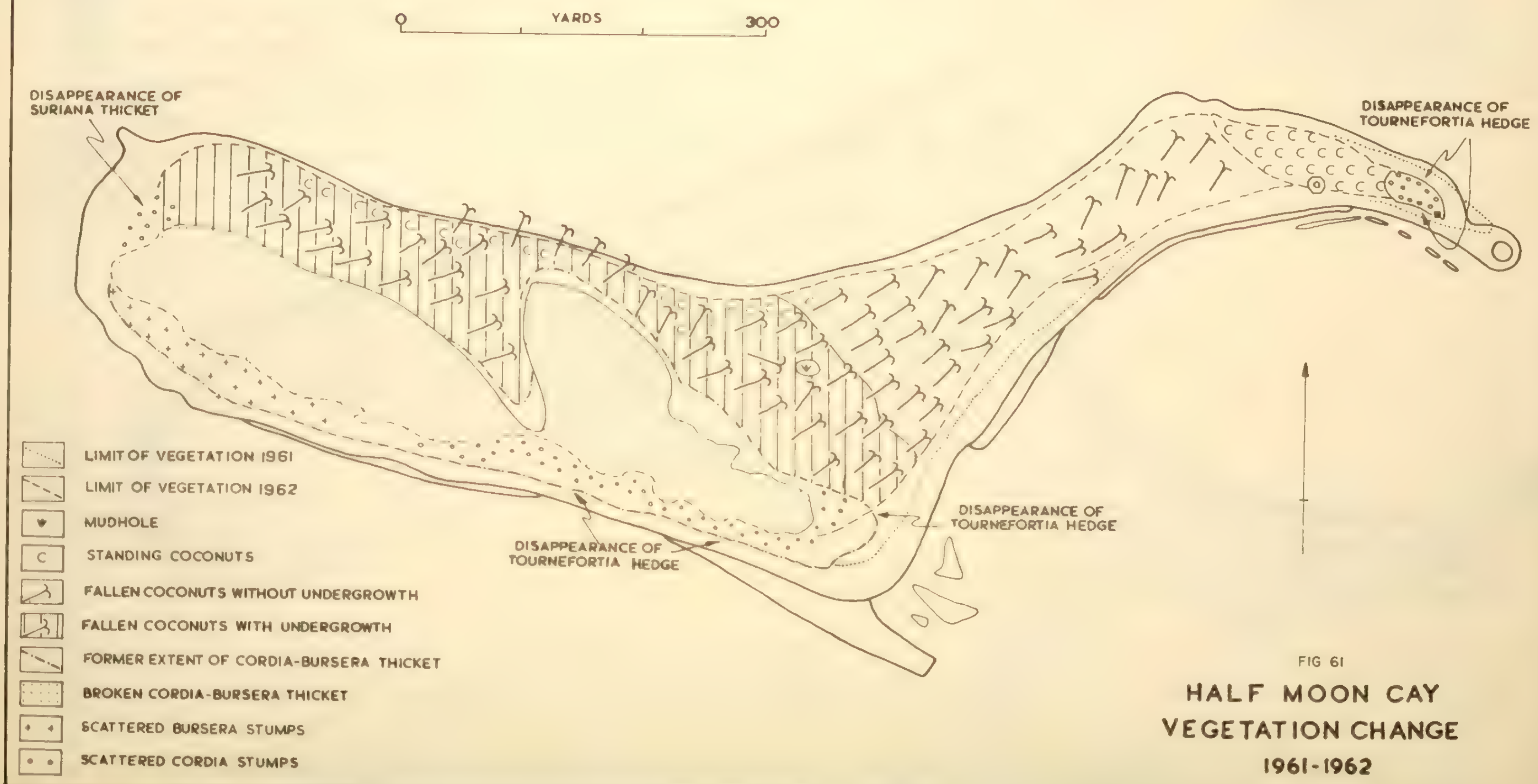


FIG 61

HALF MOON CAY
VEGETATION CHANGE
1961-1962

VIII. SUMMARY OF PHYSIOGRAPHIC EFFECTS

In the concluding chapters of this report the main physiographic, vegetational and economic changes on reef islands resulting from Hurricane Hattie will be briefly and systematically outlined. References are given to cays which well display the topics discussed, but no extended comparison is made with the few studies of hurricane effects in other parts of the world.

Zonation of Damage

From the detailed descriptions and maps of cays in Chapters 4-7, three main principles concerning physiographic change during the hurricane emerge. These are: first, damage is distinctively zoned away from the storm centre; second, damage is greater on small than on large, and on narrow than on wide islands, at any given distance from the centre; and third, damage is more intense on islands stripped of natural vegetation, or where vegetation has been much altered by man. Discussion of this third point will be found in Chapters 9 and 11.

The zonation of damage is shown in Figure 62, which is necessarily generalised. The zone of maximum or catastrophic damage extends for 15-20 miles north and south of the hurricane track. North of the storm centre winds were northwesterly, veering north and east during the passage of the storm; seas were generally north and easterly, with local northwesterly seas in the northern barrier reef lagoon (Figures 5-10 and 13). South of the storm track winds were westerly, backing south and southeast as the storm passed. Over the greater part of this area, sea level rose considerably, reaching a maximum of at least 15 feet above normal to the immediate north of the storm track (Figure 12-13), and winds throughout the zone probably reached sustained speeds of up to 150 mph. A number of small cays disappeared in this zone (Cay Glory, Paunch Cay, Cay Bokel, St. George's East Cay and others); some were completely stripped of larger plants (Sergeant's, Goff's and English Cays); the physiography was in all cases much altered, mainly by marginal erosion, stripping of surface sand, and channel-cutting; and great damage was caused to human habitations, lighthouses and jetties. Mangrove was completely defoliated, lost branches and was in places uprooted (Drowned Cays, Turneffe Islands).

North and south of this central area is a second zone, 15 miles or more wide, subject to less extreme though still very violent wind and wave conditions, but largely unaffected by the storm surge, except to an undetermined extent north of the storm track, as at Cay Caulker. Physiographic changes in this zone were generally minor, being restricted to shoreline retreat and cliffing, and minor nearshore erosion and deposition, but vegetation, especially coconut trees, suffered heavy damage. In places, as at Cay Caulker, where the vegetation had been partly cleared before the storm, waves were able to cross the cay and excavate scour holes and channels. Otherwise as at Tobacco, South Water and Chapel Cays the dominant effect was tree fall. Mangrove in this zone escaped defoliation in the centre of large islands, and in early 1962 was already beginning to recover leaves on the sides of islands in the lee of hurricane winds and waves.

A third zone includes the cays between Placencia and Gladden Spit, central barrier reef lagoon, where the main hurricane winds blew from the south with restricted fetch across water 15-25 fathoms deep. On most of these islands the vegetational effects were insignificant, but all had sand or shingle deposited on their south and east shores (as at Trapp's, Laughing Bird, Scipio and Colson Cays). Vegetation damage was only considerable on Bugle Cay, which had been cleared for coconuts: considerable shoreline retreat accompanied the destruction of the vegetation. This zone lies 30-40 miles south of the hurricane track; it is not duplicated to the north in British Honduran waters, where the barrier reef lagoon is very shallow and the cays few in number; to this extent it appears to depend on local conditions.

Finally, the cays of Glover's Reef and the southern barrier reef and lagoon suffered no vegetational and little or no physiographic damage, apart from insignificant shoreline readjustments (as at Long Cay North, Glover's Reef), which may or may not have resulted from the hurricane itself. The cays of Glover's Reef lie only 40 miles south of the storm track and the small degree of damage may result from the fact that dominant water movements were parallel in direction to the southeast reef of the atoll, on which the cays stand. At Punta Gorda, sustained gale force winds were insufficient to cause defoliation of mangrove or physiographic changes to the cays off Punta Ycacos. The zone of no damage is not found on the British Honduras Coast north of the hurricane track, except in the northern part of the Bay of Chetumal, and on the mainland Yucatan coast north of Boca Bacalar Chico, but these areas were not investigated.

Erosional Effects

Underwater

1. Damage to reef. Destruction of living corals was greatest on the barrier reef immediately north of the storm track, where up to 80% of reef corals disappeared, presumably transported by wave action into deeper water. The extent of reef damage has been fully discussed in Chapter 3 and Figure 14 and will not be repeated here. In terms of the zonation of cay damage, maximum reef damage occurred in Zone I, depending largely on exposure to waves, and to a lesser extent in Zones II and III; only in Zone III, where damage was moderate, was any large amount of reef material thrown above high tide level. Reef damage in Zone IV was negligible.

2. Submarine Slumping. The only example of submarine slumping discovered was that at Crickozeen Creek, on the west side of Turneffe Islands, between the mangrove rim and the edge of the bank, where physiographic evidence indicates rotational movement of a sector of bottom sediment (Chapter 6). It is not clear why such slumping should be so restricted in occurrence, nor what factors caused slumping at this one point.

3. Erosion of scour holes and channels. No significant change was caused to underwater topography by the hurricane; even where large scale destruction of reef corals occurred, this only extended to the removal

of a thin living veneer of reef material from the surface of reef patches. The patches themselves, and the reef flats, survive with very little change. Where such shoal areas are covered with Thalassia, it is a simple matter to observe the distribution of scour holes and channels cut through the vegetation mat. Such features can be seen at Goff's and Big Calabash Cays; they are shallow and unimportant features, with steep and overhanging sides, and it is clear that the vegetation has prevented further erosion. One is not justified in assuming that where the vegetation mat does not exist, erosion has been general, on the same scale as the cutting of the scour holes and channels; it may be that local weaknesses in the Thalassia mat have simply concentrated erosion at these points. Comparison of air photographs before and after the storm, even in areas where reef damage was extremely severe, reveals very little change indeed in shallow-water vegetation patterns (e.g. on the east side of Turneffe, at Calabash Cays and Cockroach Cays). Channel cutting has only been considerable where water movement has been restricted by islands, as between the mangrove cays of the Drowned Cays, barrier reef, or through the narrow creeks on the west side of Turneffe Islands. The overdeepened channels may be dozens of yards long and several fathoms deep, with steep and overhanging sides and meandering courses within the general meandering pattern of the creeks themselves. Where not so constricted, channels are v-shaped in plan and generally cut into the lagoon-edge of reef-flats; none have cut back more than a few yards into the reef-flat surface, and their depth is restricted. Constricted channels are now occupied by fast tidal streams, which probably limit infilling; unconstricted channels generally contain fairly still water, and may be expected to fill in fairly rapidly. Unconstricted channels are minor features; all large channels, such as those near the edge of the coastal shelf between Cays Chapel, Caulker and Ambergris, are in fact little- or un-altered pre-hurricane features.

Subaerial

1. Destruction of cays. A number of cays disappeared altogether in Zone I, including Paunch Cay, St. George's East Cay, Cay Glory, Cay Bokel, Big Calabash East II Cay, Blackbird Cay, some of the Cockroach Cays, and Saddle Cay. All of these except Paunch Cay were vegetated, though in the case of Cay Glory the vegetation only consisted of low-lying grasses, prostrate plants and a very young coconut; others had mature trees, including tall mangroves and coconuts. Most were low-lying; all except St. George's East Cay were predominantly sandy, with a little nearshore rubble, and all were small. St. George's East, a shingle cay, was the largest island to disappear: before the hurricane it was 120 yards long.

2. Marginal Erosion. Retreat of cay shorelines has taken place in Zones I, II and III. All material above sea level and for several inches below it has been eroded away, in a zone up to 20 yards in width, generally greatest near the hurricane centre and on the side of the cay facing main hurricane winds (east to the north of storm centre, southwest to the south). This has left a vertical cliff, usually 1-2 feet high, capped by a mat of coconut roots from which all sand has been flushed. In places this cliffed shoreline is fairly straight; often the presence of near-shore coconut boles holding up promontories has given it an intricate

outline. Occasionally one finds pillar-like remnants of the old cay standing outside the present cliff-line, as at Soldier and Big Calabash Cays; these too are steep-sided and capped with coconut roots.

3. Destruction of unconsolidated spits. This was probably universal throughout Zones I - III, but by early 1962 fresh spits of similar general form had in most cases regrown at or near the old location, as at English Cay.

4. Channel-cutting. Cutting of channels through cay surfaces was limited to Zone I, in the area covered by the high sea surge, and to cays with coconut or other thin ground vegetation. Scouring of deep channels occurred at St. George's Cay, and shallower channels at Mauger and Sandbore Cays, all across narrow necks of land. Incipient channels were seen at Half Moon Cay and Deadman V Cay, extending headward from the lee side of cays, and at Cay Caulker, where roadways transverse to the seaward shore were overdeepened in the village.

5. Scour holes in cay surfaces. Erosion of scour holes by overtopping waters was widespread in Zones I - III. They were generally developed at the margin of some obstacle to water flow, such as buildings (Sandbore Cay) or the upturned boles of trees, using as a nucleus the holes left by roots. Holes at Cay Caulker are elongate and not apparently related to any obstacle. At Half Moon Cay scour holes were seen in the lee of shingle ridges deposited by the hurricane itself. Scour holes have also been seen along the lee shores of cays, where overtopping waters reached the lagoon (Cay Chapel, Cay Caulker).

6. Stripping of surface sand. Where cays were overtopped by the storm surge in Zone I or had their margins submerged by heavy wave action in Zones II - III, stripping of loose surface sand was almost universal, though generally confined to a narrow marginal strip up to 30 yards wide, immediately inland from the undercut cliff-line. Decrease in elevation was generally less than 1 foot, but this involved the removal of all or most surface sand and soil, revealing long coconut roots and occasionally orange Thrinax roots. These are sometimes combed in the direction of water movement, as at Deadman V and Big Calabash Cays. Frequently in Zone I the coconut roots form a surface mat several inches thick, devoid of sand though littered with fresh debris; in Zones II - III, however, the exposed root mat is much thinner and rests on tightly packed sand, as at South Water Cay.

7. Erosion of consolidated deposits. Beachrock has been remarkably successful in resisting erosion, especially underwater. However, at Half Moon Cay, where the conglomerate platform is much pitted and eroded, wave smoothing is apparent on the surface, where several large projecting blocks have been torn away. In the southeast bay the outer margin of the beachrock has suffered considerable damage; large plates were broken off and thrown onto the shore or uptilted in the water against the unbroken beachrock. The only consolidated deposits to disappear were incipient beachrocks of small extent, such as a beachrock seen in 1961 near the north point of Northern Cay. Clearing of algal mats on beachrock also revealed much fracturing, which may have existed before the hurricane.

8. Uprooting of coconut trees in Zones I - II could leave holes in the cay surface up to 3 yards in diameter and 3 feet in depth, which were liable to scouring by waves near the shore. These holes may reach the water table, and many are now filled with water, giving surface a pock-marked appearance, as at Long Cay, Lighthouse Reef.

9. Finally, cliffing and undercutting of sand areas could take place well above sea level during violent wave activity, as on the southeast sand ridge at Half Moon Cay, where undercutting and ridge retreat has formed a vertical cliff 4 feet high just below the ridge crest and 20 yards from the sea.

Depositional Effects

Underwater

1. Deltas and deposition cones of sand at the mouths of scour channels between cays, as at Drowned Cays, and at the leeward end of creeks, as on the west side of Turneffe, are found in Zones I - II.

2. Deposition cones are also found at the leeward ends of scour channels cut through cay surfaces. They are beautifully developed at St. George's Cay, Zone I.

3. Shoaling in nearshore areas, by deposition of material eroded from cay surfaces, especially sand. This is well seen in the Sandbore Cay lagoon, Zone I.

4. Scattering of large blocks on reef flats. In view of the great destruction of reefs it is surprising that so-called 'negro-heads' or reef-blocks throw up onto reef-flats during the storm are almost non-existent. Immediately after the storm it is said that more small reef debris was visible above sea level, at least on the northern barrier reef, but by early 1962 most of this had disappeared. Only at Big Calabash Cay, Turneffe, and Cary Cay, central barrier reef lagoon, are any large blocks now stranded on reef-flats.

5. Deposition of rubble carpets. This is much more widespread in Zones I - III, though the amount of deposition is still small compared with Jaluit. Carpets are best developed along the old reef crest, where they rise to within a few inches of the surface, occasionally emerging as low ridges, and terminating lagoonward in steep faces. They are best seen along the barrier reef, as at Cay Glory and Carrie Bow Cay, and on the Turneffe east reefs. In places the shingle lacks this well-defined ridge form and is spread in a thinner, wider carpet, with imbricate palmata slabs, as at Goff's Cay.

6. Ephemeral reef-crest shingle ridges consist only of the emergent portions of these carpets. None are more than 3 feet in height and most only a few yards long. Immediately after the hurricane they may have been more extensive than when seen in early 1962. The ridges at Soldier Cay, Carrie Bow Cay and Skiff Sand are probably in the process of destruction.

7. Presumably the great amount of reef material destroyed in Zone I has been swept into deeper water on the seaward and lagoonward slopes of reefs; much of it may lie at depths of 50 feet or more. Much vegetable material has also been dumped in deeper water: in the northern barrier reef lagoon trees are seen on the lagoon floor and even emerge above the surface at distances of several miles from cays. No investigations were made of conditions on lagoon floors or in deeper water.

Subaerial

Submarine depositional features are of minor importance, and with the exception of the St. George's Cay deltas, none are spectacular. Subaerial depositional features are physiographically significant, more so in some areas than in others. They are not well developed in Zone I on the barrier reef, but are found in the same zone on the east side of Turneffe; they reach their most typical development in Zone III, where erosional effects are minimal. Part of the difference in Zone I lies in vegetation: on the barrier reef the cays were low, small and coconut-covered. With the coconuts swept away, and submerged by the storm surge, the island itself would present little obstacle to the passage of sediment. On the atolls, however, most of the cays were densely vegetated and most of the vegetation remained in place during the storm, acting as a barrier to sediment movement and resulting in the piling-up of debris. To illustrate this one may contrast the mainly depositional effects at Cockroach II (Pelican) Cay, covered with Bursera-Cordia bush; and the different picture at Cockroach Cay itself, covered with easily-destroyed coconuts, where most surface sand was stripped, no shingle ridges were built, and deposition was limited to accumulation of sand in the leeward bay. There is a similar contrast between deposition on the Cordia-Bursera covered south shore of Half Moon Cay, and erosion on the coconut-covered southwest shore. Finally, in Zone III one may contrast the widespread deposition on densely vegetated islands such as Colson, Scipio, Cwen, Trapp's and other cays, and the considerable erosion on Bugle Cay, which had been cleared for coconuts. Subaerial deposition takes the following forms:

1. Littering of heavily eroded surfaces with coarse coral rubble, often of small calibre, as at Cockroach Cay and Sandbore Cay, Zones I and II.

2. Accumulation of coral shingle and sand against vegetation barriers: this occurs at Cockroach II and Half Moon Cays (where debris is piled up to a height of 10 feet above sea level), and on several of the central barrier reef cays, such as Cwen and Laughing Bird Cays.

3. Deposition of wider, thinner carpets, generally of sand, on the cay surface, especially inland from the marginal erosion zone already described, in Zones II and III. This feature is typically seen at South Water, Trapp's, Scipio and Colson Cays. The carpet may be up to 30 yards wide, wedging out seaward and thickening landward, terminating on the landward side in a steep face, often arcuate in plan. The sand buries the old cay surface, which may retain its vegetation and soils, to depths of up to 2 feet. Even where the sand is deepest the taller vegetation may protrude through it and survive (especially Thrinax); where thinner, Hymenocallis is often still visible and living. Such carpets were seen at Placencia

in 1961 on the day they were deposited by Hurricane Anna. Burial of old soil horizons by carpets, mostly of rubble, was described at Jaluit after Typhoon Ophelia (Blumenstock, editor, 1961); in British Honduras rubble carpets are distinctly rare, except where they form parts of ridges piled against vegetation barriers, as at Cockroach Cays.

4. Deposition of shingle ridges round the old cay shore, which may itself have suffered erosion. Again, these are typically developed in Zone III, where the ridges may or may not adjoin the old shore for all their length. In places the main ridge may lie some yards to seaward, enclosing a low-lying shingle carpet or open water between it and the eroded shore (Colson, Scipio, Trapp's Cays). In this case the calibre of the material is coarsest in the ridge, and much finer in the enclosed zone. These offshore ridges may pass laterally into ridges built against and on the shore itself.

5. Extension of leeward shores by sand deposition. This was noted by mapping at Cockroach Cay and Deadman I Cay along the greater part of the leeward shore; minor extensions of shorelines by deposition was also noted at Half Moon Cay and elsewhere.

Incidental Physiographic Effects

The most important incidental physiographic effect on cay physiography was the increase in number of outcrops of cemented sands. These have been described individually in this report, and in general terms in ARB 87, 106-109. They may be grouped as follows:

Intertidal beachrock

The name 'beachrock' is here restricted to the narrow strips of cemented beachsands, which generally dip seawards, following the line of the shore, are of very limited vertical extent, and are characteristically found on retreating beaches or on reef-flats marking the sites of former shorelines. In British Honduras beachrock and beachsands contain much Halimeda and encrusting red foraminifera. New exposures resulting from Hurricane Hattie were of three types: (a) old relict beachrock covered with later sediments has been re-exposed, as at Goff's Cay, Carrie Bow Cay, and partially at Paunch and Curlew Cays. (b) Incipient beachrock noted in 1960-61 has been revealed by shore retreat and stands away from present shore as true relict beachrock; this is well shown on the lee shore of South Water Cay and the south shore of Sandbore Cay. (c) In other areas shore retreat has revealed beachrock the existence of which was not previously suspected. This is well shown on the lagoon shore of Sandbore Cay, and in the peculiar islandward-dipping beachrock on the seaward shore of Carrie Bow Cay. None of this beachrock stands above or below its intertidal location; its position reveals horizontal shifts in shoreline location only. At Carrie Bow Cay, two lines of fresh beachrock have been revealed marking the position of a former ephemeral sandspit, which in 1960 was subject to overtopping by waves: it is difficult to see how fresh groundwater could have played any part in the formation of this rock, in the manner Russell (1962) has described. Most of the new intertidal beachrock varies considerably in degree of cementation, but all

consists of typical beachsands. The reverse-dipping beachrock at Carrie Bow Cay is well-cemented, that marking the ephemeral spit is very soft. Many of the softer exposures, especially on seaward shores, may not survive against wave attack for a sufficiently long period for the secondary cementation which Russell indicates is necessary for complete lithification. No fresh beachrock anywhere in British Honduras approaches the toughness of long-exposed examples, such as that at Half Moon Cay. Examination of hand samples shows that freshly exposed beachrock consists of loosely bonded particles in a very friable cement, with many open spaces; whereas in older beachrock the grains are tightly cemented into a solid mass with few interstices, except where the grains are large, dominantly Halimeda, where interstices still remain open.

While it is true that beachrock exposures are only associated with retreating beaches, as Seymour Sewell (1935, 511) and Stanley Gardiner (1930, 16) recognised, the British Honduras data shows quite clearly that massive beachrock may form on stable, and even aggrading shores, as on the interior lagoon beach of Sandbore Cay. In this instance, the thickness of beachrock on the stable lagoon shore much exceeds that on the eroding seaward shore. Beachrock clearly forms beneath beaches, not at the surface; where incipient beachrock outcrops at the foot of beaches, it may be traced inland beneath beach sands, in the same way in British Honduras as mapped by Russell elsewhere in the Caribbean. The cause of reverse dip in beachrock is unknown: its occurrence at Carrie Bow Cay and Southwest Cay II, Glover's Reef (ARB 87, 97), suggests that it may be a more widespread phenomenon than previously recognised. Widespread evidence of retreat of cays across reef flats suggests that reversed beachrock may have been formed on lagoon beaches and exposed on seaward shores as the cay retreated completely across it; but such an interpretation needs more substantial evidence. The role of beachrock as a stabilising element in cay physiography has often been stressed: thus Steers (1937, 12) writes that "the formation of beachrock on any coral islet off the Queensland coast is a stabilising factor, and the permanency of an islet probably depends more on this factor than on any other". The presence of many exposures of relict beachrock off present cay shores shows that this protection is at best imperfect; during Hurricane Hattie no instance was seen where the presence of beachrock restricted shore retreat, when compared with nearby areas lacking beachrock. By contrast, well-developed and undisturbed natural vegetation appeared much more effective in cay preservation.

Cay Sandstone

Cementation of cay sands above sea level was described by Kuenen (1933, 86-88) and Seymour Sewell (1935, 502-512), but on account of its less distinctive characteristics and infrequent exposure it has not often been described. Moresby (1835, 159), Seymour Sewell (1935, 502-512) and Stanley Gardiner (1907) noted it in the Maldive Islands, where Gardiner termed it "tuffa"; Kuenen also noted it in the East Indies (1933; 1950, 434-435). Following Hurricane Hattie, there is little doubt that rock exposures on the British Honduras cays formerly interpreted as possible raised beachrocks are in fact cay sandstones. Such rocks are best exposed at Harry Jones Point and Big Cay Bokel, Turneffe. The rock has an almost horizontal upper surface, but may dip laterally along the beach with

variation in the height of the cay surface itself. The upper surface is smooth when fresh, but becomes blackened, pitted and eroded on exposure to the atmosphere. Undermining after exposure along the shore may lead to the breaking off of slabs of rock, which then lie on the shore at the angle of the beach, and where thin may be confused with intertidal beachrock. This is well seen at Northern Cay, Lighthouse Reef. Typically, cay sandstone lacks the large unbroken Halimeda grains, large fresh red Homotrema, and distinctive vertical size-grading of intertidal beachrock. Its constituents are finer, and the cementation in fresh samples is superficial and poor. After exposure it appears that a secondary cementation takes place, analogous to that which Russell demonstrates for intertidal beachrock (1962), resulting in a tough, ringing rock; this was in fact noted long ago by Moresby (1835, 400).

Cay sandstone is normally exposed by retreating shores; at Cay Chapel it has been revealed by stripping of surface sand across the front slope of a beach ridge. Here it forms an inclined plate, dipping seaward though well above sea level, and still very friable. After four months of exposure the surface was etched into hole-and-ridge patterns often associated with wind erosion in deserts (Cotton, 1942). Nearby, the same rock is seen in a beach scarp, covered with 12 inches of uncemented sand and soil, with vegetation. Similar though weaker cementation was seen at Cay Caulker, in overdeepened roads transverse to the seaward beach. Nowhere was cay sandstone seen to be overlain with more than 3 feet of uncemented sand. It is presumably associated with percolation of rainwater to the water-table, and was not seen on any cay without a known fresh-water lens.

The recency of the cementation, and formation at the present altitude are beyond dispute. At Harry Jones, cay sandstone contains Maya pottery. Most newly exposed surfaces contain coconut roots within the rock matrix. At the inner edge of the exposed area, these roots may be followed up into overlying undisturbed sand. Further, cementation beneath cay surfaces is less advanced than on exposed areas: this is well shown by a scour hole cut through the cay surface into underlying cay sandstone at Northern Cay, Lighthouse Reef (Figure 63). Here a weak horizon of cementation was exposed on all sides of the scour hole, with uncemented sands both above and below. Outcrops of cemented material, too restricted to determine form, as at South Water Cay, are here interpreted as cay sandstones, rather than resort to hypotheses of warping or eustatic fluctuations of sea level. It should be noted that this re-interpretation of the Harry Jones exposure removes what evidence there was for movements of this kind at Turneffe Islands (ARB 87, 109-111): no feature of these cays now requires any recent high stand of the sea in explanation of it.

Promenade Rock

This name is used here for the cemented material comprising a restricted topographic feature, the promenade, described by Steers initially from the Great Barrier Reef Islands (1929, 252-256; 1937, 27, 119) and in greater detail for the Morant Cays, Jamaica (1940a, 39-40: 1940b, 309). At Morant Cays Steers found platforms with eroded, horizontal upper surfaces, showing no apparent dip, 12-18 inches above sea level, composed

of beach sands and similar to true beachrock. The rock surface appeared to be recemented and was much harder than the interior. Promenades always occurred on the windward sides of cays. The similarity of these promenades with the conglomerate platform at Half Moon Cay has been previously noted (ARB 87, 107). During Hurricane Hattie, low-lying platforms of cemented sand and rubble were exposed by severe shoreline retreat at Deadman I and II Cays, Turneffe, where previously only a small patch of supposedly incipient beachrock had been seen. These resemble the Half Moon Cay exposures in everything except degree of cementation. It appears that cementation of sands, shingle and rubble must take place beneath cays at and slightly above sea level, and that this cemented material has been exposed by erosion. The cementation is sufficient to preserve the form of the promenade, but not for the collection of specimens. As in the case of beachrock and cay sandstone, it seems likely that secondary cementation occurs once the promenade is exposed, to transform it into solid resistant rock. Whether the Deadman exposures will survive long enough for the secondary cementation to take place has yet to be seen. As in the case of cay sandstone the important conclusion is that promenades form beneath cays at their present elevations: and that they are not indicators of relative change in land or sea level. This explanation does not preclude the possibility that elevation or depression has occurred, through tectonic or eustatic causes; but it does mean that without other evidence, promenades and cay sandstone exposures are not in themselves sufficient indicators of such movements.

Shingle Rock

At Cockroach Cay II the exposure of a very coarse shingle rock, cemented by a brownish cement, has been described in Chapter 6. The cement appears superficially similar to that in the central part of Half Moon Cay, and in the two fresh exposures of the same rock on that island. At Cockroach II the present topographic form of the shingle rock is similar to that of the Cay Chapel cay sandstone: it lies on the face of the beach ridge, is restricted in area with very steep sides, and dips seawards. The main point of difference is in the brown cement. In this connection it is interesting to note that both islands where this occurs have substantial areas of Cordia-Bursera bush.

Other Rock

Finally, surface incrustation of sands, perhaps resulting from inundation by salt water during the hurricane, has been described at Sandbore Cay, Lighthouse Reef. This is very friable and thin, and there is no evidence that lithification will proceed sufficiently to form a significant topographic feature.

Apart from the Cockroach II shingle rock and the interior cementation at Half Moon Cay, cemented materials on cays appear to consist of cay sandstone, promenade rock, intertidal beachrock, and a few other exposures which may be intermediate between these groups. Seymour Sewell was "by no means fully convinced" (1935, 501) of the distinction between cay sandstone and beachrock. Cay sandstone formation is apparently associated

with fresh water percolation (Kuenen, 1950, 434-5); and Russell (1962) has recently assembled evidence to show that primary cementation in beachrock formation is also associated with the presence of a freshwater lens. While there are many examples, some cited in this report, where it is difficult if not impossible to accept the role of freshwater in beachrock formation, chiefly on locational grounds, it is pertinent to enquire, if Russell is correct in the cases he describes, what the essential differences are between intertidal beachrock and other rocks associated with fresh water but developed well above high tide level. If there is, in fact, no essential difference, then the usefulness of beachrock as a reliable indicator of changes of level must be very much reduced, in spite of the fact the field exposures of the two types of rock are characteristically completely different.

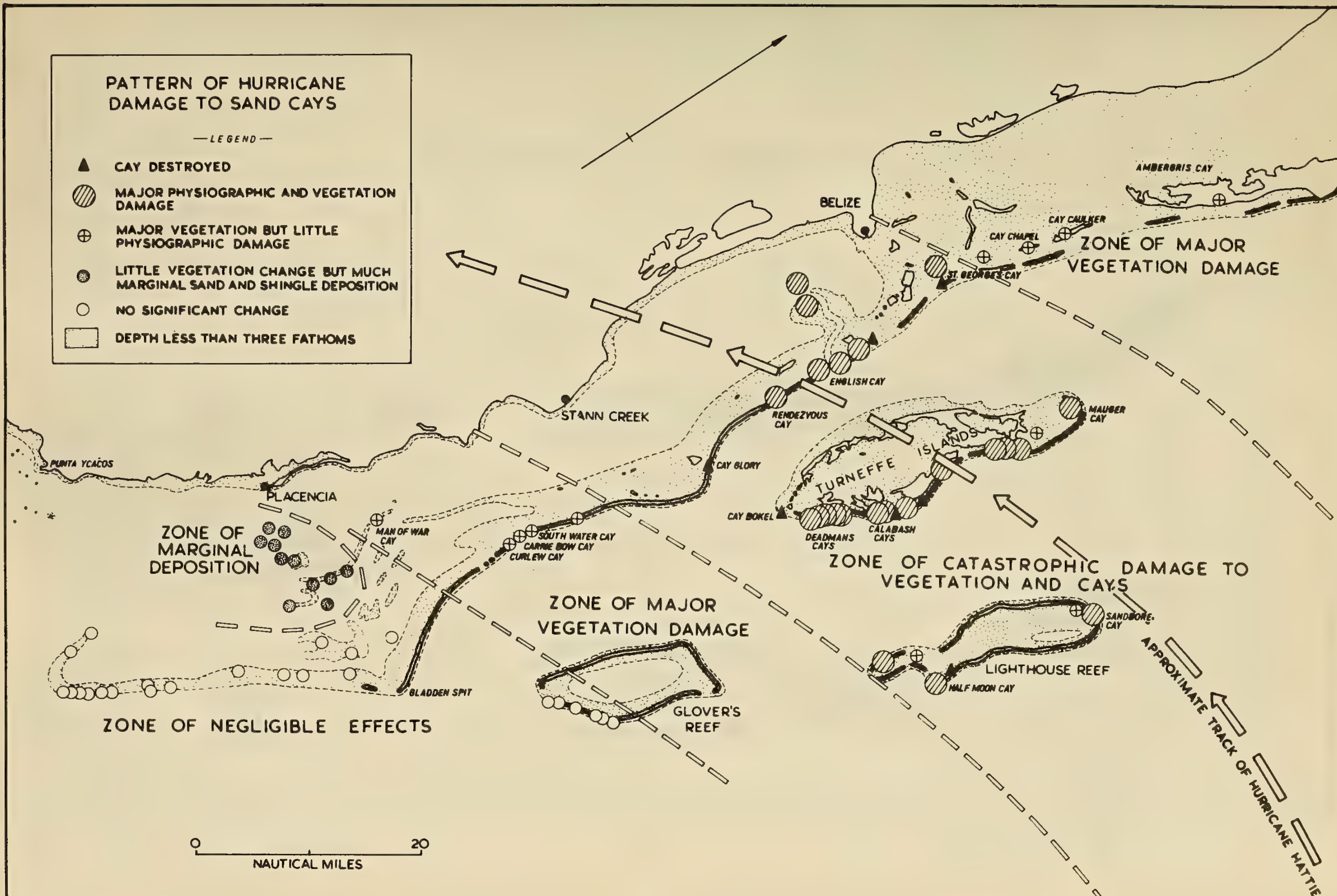
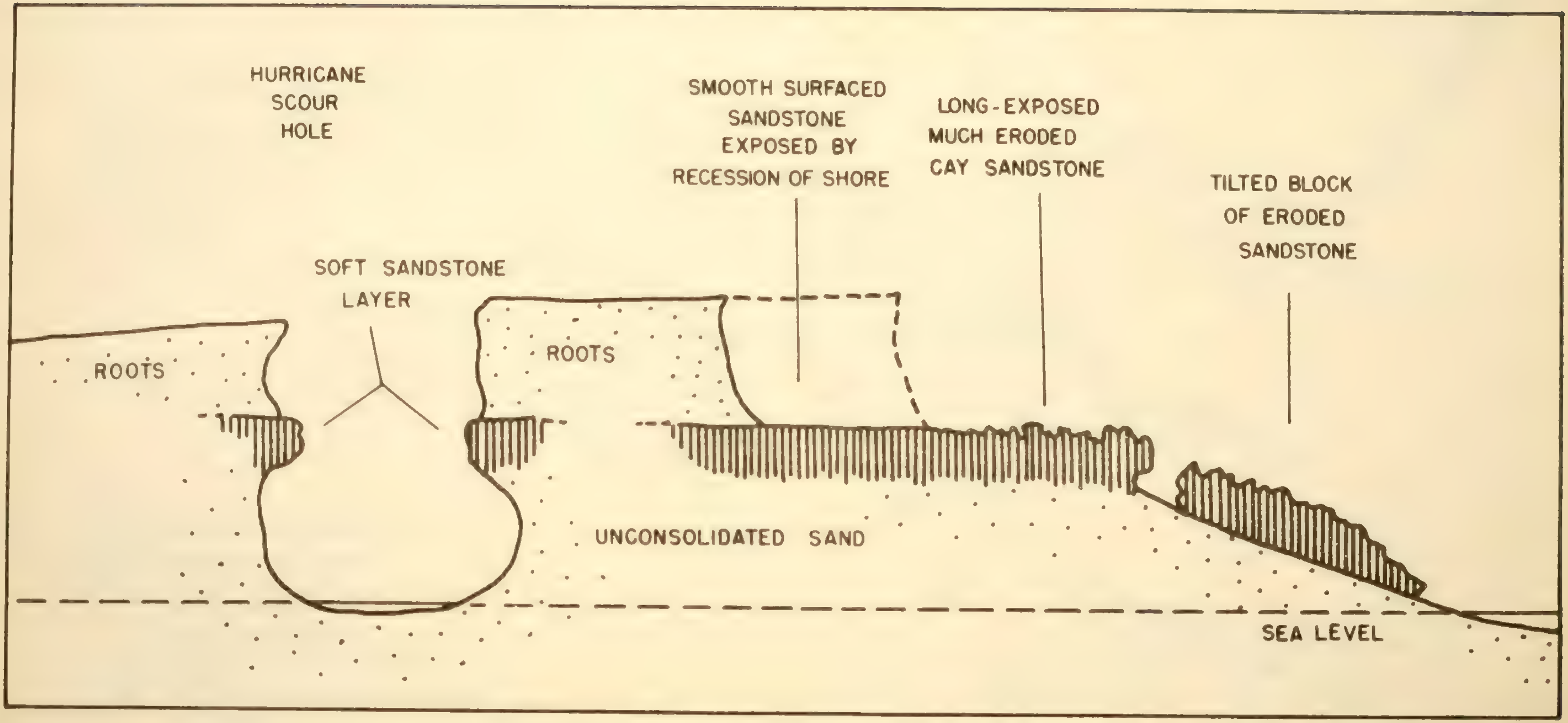

PATTERN OF HURRICANE DAMAGE TO SAND CAYS
—LEGEND—
CAY DESTROYED
MAJOR PHYSIOGRAPHIC AND VEGETATION DAMAGE
MAJOR VEGETATION BUT LITTLE PHYSIOGRAPHIC DAMAGE
LITTLE VEGETATION CHANGE BUT MUCH MARGINAL SAND AND SHINGLE DEPOSITION
NO SIGNIFICANT CHANGE
DEPTH LESS THAN THREE FATHOMS
AMBERGRIS CAY
BELIZE
CAY CAULKER
CAY CHAPEL
ZONE OF MAJOR VEGETATION DAMAGE
ST. GEORGES CAY
ENGLISH CAY
RENDEZVOUS CAY
MAUGER CAY
TURNEFFE ISLANDS
STANN CREEK
CAY GLORY
CAY BOKEL
DEADMANS CAYS
CALABASH CAYS
PUNTA YCACOS
PLACENCIA
ZONE OF MARGINAL DEPOSITION
MAN OF WAR CAY
SOUTH WATER CAY
CARRIE BOW CAY
CURLEW CAY
ZONE OF CATASTROPHIC DAMAGE TO VEGETATION AND CAYS
ZONE OF MAJOR VEGETATION DAMAGE
SANDBORE CAY
LIGHTHOUSE REEF
HALF MOON CAY
BLADDEN SPIT
GLOVER'S REEF
ZONE OF NEGLIGIBLE EFFECTS
APPROXIMATE TRACK OF HURRICANE HATTIE
0
20
NAUTICAL MILES

FIG. 62



Section of Cay sandstone at Northern Cay

FIG. 63

IX. VEGETATIONAL EFFECTS OF THE HURRICANE

Vegetation Types and Zonation of Damage

Damage to vegetation at any place during the hurricane depended on the local storm conditions (largely a function of distance and direction from the storm centre); whether the vegetation was affected by direct submergence and wave action or by the wind alone; the type of the vegetation; the species involved; and the nature of the substrate. The main vegetation types of the British Honduras cays correspond quite closely with those described for the Florida Keys by Davis (1942) and the Jamaican cays by Asprey and Robbins (1953). We may briefly differentiate the following types:

1. Beach vegetation, locally differentiated according to substrate and exposure.

2. Interior vegetation on cleared sand cays.

3. Marginal vegetation, forming a low thicket at the top of the beach, between the beach vegetation and the interior woodland or palm thicket; differentiated according to substrate and aspect.

4. Woodland, mainly Cordia-Bursera thicket.

5. Palmetto woodland, mainly Thrinax.

6. Coconut plantations, with or without undergrowth. Other introduced plants are grouped as Type 6a.

7. Acrostichum marsh.

8. Rhizophora marsh.

9. Avicennia woodland.

10. Interior vegetation on dryland areas of sand-mangrove cays.

11. Submarine vegetation.

1. Beach vegetation

This typically consists of prostrate vines, low herbs and some grasses (Sauer, 1959). Species include Ipomoea pes-caprae, Sesuvium portulacastrum, Euphorbia mesembrianthemifolia, Cakile lanceolata, Vigna luteola, Sporobolus virginicus. Damage largely depended on the degree of hurricane modification of the substrate itself, and to a lesser extent on direct effects on plants. Thus if a beach has been shifted landward and vertically

eroded, the vegetation on it will obviously have been destroyed. Near-shore vegetation on exposed beaches in Zones I - III was therefore damaged, the destruction extending right across the island in the case of some cays in Zone I. Where inundation occurred without beach erosion, the best survivors are the grasses; other plants such as Ipomoea and Sesuvium seem to have been swept away by wave action.

2. Interior vegetation

Except where artificially cleared, most cay surfaces beneath coconuts are covered with a low mat of herbs, grasses, etc., often in distinct zones. Species include Stachytarpheta jamaicensis, Ipomoea pes-caprae, Canavalia rosea, Euphorbia mesembrianthemifolia, E. blodgettii, Cyperus planifolius, Fimbristylis cymosa, Wedelia trilobata; grasses such as Eragrostis, Sporobolus and Andropogon; bushes such as Ernodea littoralis, Erithalis fruticosa and Rivina humilis; and the lily Hymenocallis littoralis. Near the margins, especially of small cays in Zone I, damage resembles that to beach vegetation: sand-stripping and deposition of sand and shingle may destroy or damage vegetation over a peripheral zone up to 60 yards wide, but generally less than 20 yards wide in Zones II - III. In Zones II - III the interiors of cays were not submerged by the storm surge and the ground vegetation suffered no considerable change. Clearly, therefore, the relative amount of marginal destruction and lack of change in the interior will depend on the size and shape of the cay concerned. Burial near cay margins appeared to kill all plants except trees and the lily Hymenocallis, which often protrudes through sand carpets.

3. Marginal vegetation

This rather unsatisfactory name is applied to a typical vegetation of bushes 3-6 feet tall at the top of the beach, forming a transition zone between the beach vegetation and interior woodland or coconuts. Constituent species differ with substrate and aspect: Tournefortia gnaphalodes is typical on exposed shores, especially on shingle, Suriana maritima on more protected shores, especially on sand. Other bushes, often stunted, include Coccoloba uvifera, Borrichia arborescens and Conocarpus erectus, with Sporobolus, Hymenocallis and other low beach and interior plants. In Zone I, where the rise in sea level and violence of wave action both reached a maximum, this vegetation type has disappeared. Re-location of beaches has destroyed all mature Tournefortia and Suriana on Lighthouse Reef, Turneffe Islands and the northern barrier reef. Sophora tomentosa has also disappeared in this zone. Damage in Zones II and III was much less, but even at South Water Cay, where beaches suffered little change, Tournefortia and Suriana have markedly decreased through wave action.

4. Woodland

This group includes the remnants of a presumably once more extensive cover of woodland and thicket on the cays, the greater part of which has

been removed for coconuts since the European occupation. It typically consists at Half Moon and Cockroach Cays of dense, often spray-swept thickets of Bursera simaruba and Cordia sebestena, forming a canopy at a height of 20-30 feet. On Half Moon Cay at least there is little or no ground vegetation beneath the thicket. Coccoloba is found round the margins and Ficus and Neea towards the interior of the thicket. In Zone I damage to this thicket was of two types: direct wave damage round the margins and wind damage in the interior. The first, which often involved erosion and deposition of beach material, led to uprooting of trees or stripping of sand and soil from their roots. Consistently in these circumstances Bursera remained in the position of growth better than Cordia; Coccoloba was also seen uprooted, though generally still in situ. Nearshore trees not uprooted generally lost all their leaves and most branches and many are now only twisted and broken stumps. At the limit of wave action on larger islands trees were buried by shingle, as at Half Moon and Cockroach Cays. The interior part of the woodland which escaped wave action also lost all or most leaves and many branches; as a result I estimate that the height of the canopy at Half Moon Cay decreased by at least 50% as a result. Larger trees such as Ficus were uprooted and overturned. However, in early 1962 leaves were returning to those trees affected only by wind action, in contrast to those which suffered inundation and wave attack. In Zones II and III it is difficult to evaluate hurricane effects on woodland as a whole, apart from individual species, because of its poor development. Judging by individual species, damage in Zone III was negligible.

5. Palmetto woodland

This is a localised type, characterised by stands of Thrinax parviflora similar to those on the Jamaican coast (Asprey and Robbins, 1953, 373). It is confined, at least in pure stands, to seaward shores, and is only well developed in Zone III. Even in nearshore locations most palmettoes survived, even where partly buried by sand and shingle deposits. Thrinax appears more resistant than Cocos to wave and wind action.

6. Coconut plantation

This is the dominant vegetation on sand cays, coconuts having been observed on Lighthouse Reef in 1720 (ARB 87, 63-64), noted on Glover's Reef in 1804 (Henderson, 1812), and being widespread on the barrier reef as early as the second half of the eighteenth century. Coconuts were totally destroyed where cays were washed away during the hurricane, and wherever shorelines were relocated. Post-hurricane shores in Zones I - III are generally lined by fallen trees, giving rise to a miniature cape-and-bay outline. Away from the effects of wave action, wind felled approximately 75% of all trees in Zone I and at least 50% over most of Zone II. Direction of tree fall is shown in Figure 64, which shows a good correlation with the direction of first hurricane-force winds (cf. Figures 6-10); note however that many of these observed directions are influenced by wave action. It seems likely that most tree-fall occurred during these first hurricane-force winds, rather than - as Wiens suggests (Blumenstock, editor, 1961, 21) - during most intense hurricane winds.

In British Honduras these often seem to have followed the storm centre, and would have given directions of fall the opposite of those observed. In Zone I tree fall occurred either by uprooting or snapping above ground level; many trees stood but lost their crowns. In Zones II - III uprooting was most evident along shorelines. Damage to coconuts in Zone II appears to decrease more rapidly north of the storm track than south of it. Thus, while many trees were felled at Cay Chapel, fewer came down at Cay Caulker, where even young trees survive at the edge of the seaward beach; damage was very slight at Ambergris Cay. Cay Caulker is the same distance north of the storm track (25 miles) as Tobacco and South Water Cays are to the south; at the latter islands, 70-80% of the coconuts fell, perhaps partly reflecting the reportedly stronger southerly winds. Many nuts were strewn over non-inundated surfaces, but had not germinated in early 1962. Vegetation under coconuts suffered little damage away from storm surge areas. Most species still survive (see type 2).

6a. Introduced plants

Introduced plants are generally associated with human settlement. *Terminalia catappa* is one of the most widespread, and survived in Zone II even in nearshore locations; it was not seen before the hurricane in Zone I. *Musa paradisiaca* was destroyed at Cay Caulker and at coastal settlements near Mango Creek, both in Zone II. Tall pines and a mango tree were overturned at Cay Caulker.

7. Acrostichum marsh

This is limited to the cays of the central barrier reef lagoon and the southern barrier reef (Zones III, IV); it appears to have suffered no ill-effects except where locally buried by sand or shingle near shorelines. *Acrostichum* inland from Belize (Zone I) is still living.

8. Rhizophora marsh

The major part of mangrove and mangrove-sand cays consists of *Rhizophora*, which is also found in small quantities round the shores of some sand cays. In Zone I both nearshore and interior *Rhizophora* was exposed to inundation and severe wave action; elsewhere interior *Rhizophora* was affected by wind alone. Throughout Zone I mangrove was completely defoliated, damage being greatest on windward shores and on small islands. In the interior parts of the Turneffe mangrove defoliation was less severe, and trees had regained some leaves by early 1962. This suggests that inundation and direct wave action play a large part in leaf stripping and perhaps in killing individual trees. On smaller islands, and on the Turneffe mangrove areas, the beginnings of leaf re-growth on the leeward sides of cays (i.e. west side to the north and east side to the south of the storm track) was noted in April-May 1962 at points north of St. George's Cay; and at Southern Long and Cross Cays. These points are respectively 12 miles north and south of the storm track. Within this zone, about 25 miles wide, defoliation was total on small cays, and none at this time showed signs of regeneration. Individual plants were liable

to defoliation as far south as Laughing Bird Cay, nearly 40 miles south of the hurricane centre, but a high proportion of mangroves escaped defoliation at distances of 30-40 miles from the centre. After the hurricane, mangrove cays in the most devastated area had a distinctly reddish appearance from the air, and destruction of the leafy canopy revealed large areas of standing water and bare mud, particularly in the Drowned Cays and islands northwest of Belize. Individual *Rhizophora* trees showed extraordinary stability, typified by the survival of a dead *Rhizophora* ring at Big Calabash Cay II and Blackbird Cay, where the enclosed island disappeared under wave attack. Seedlings, on the other hand, disappeared in large numbers, and had not re-appeared in early 1962. The details of mangrove cay topography, especially shoreline form seen in plan, are virtually unaltered by the hurricane, as air photographs demonstrate.

9. *Avicennia* woodland

This is insufficiently developed on the cays affected by the hurricane to merit separate comment. Like *Rhizophora* it suffered defoliation in Zones I - II, and in exposed situations was liable to overturning, loss of branches and reduction to a stump.

10. Interior vegetation on cleared mangrove cays

Many mangrove cays have small dryland areas with coconuts and ground vegetation, as at Mauger Cay, Weewee, South Rendezvous Cay and Cat Cay. Typical plants include *Batis maritima*, *Cyperus planifolius*, *Chloris petraea*, *Euphorbia* sp., *Conocarpus*, *Coccoloba*, and *Thespesia populnea*. Except where inundated by the storm surge, and apart from overturning of coconuts and other tall trees, damage to this vegetation was slight, and comparable to Type 2, Interior vegetation of sand cays. Where inundated, as at Three Corner Cay and Mauger Cay, large shrubs were liable to uprooting and all plants to destruction by surface sand scouring and channel-cutting.

11. Submarine Vegetation

No systematic observations were made on submarine vegetation. Throughout Zone I larger algae, including *Halimeda*, disappeared from beachrock and other rocky surfaces near sea level. *Thalassia* leaves appear to have been stripped by wave action in places, and piled on beaches, as at Northern Cay, Lighthouse Reef, but apart from scattered channel-cutting and hole-scouring, the turf mat was not disturbed.

Summary of Vegetational Effects

Factors leading to vegetation damage thus include:

(a) inundation, limited to a narrow zone north of the storm track and to lower margins of cays;

(b) direct wave action on marginal vegetation and across the entire area of small cays;

(c) effect of water-born boulders and other debris;

(d) horizontal erosion of beaches, greatest in Zone I, also in Zones II - III;

(e) surface stripping of sand, with consequent removal of vegetation and exposure of roots: Zones I - III;

(f) burying by fresh deposits of shingle and sand, common in marginal areas of densely vegetated islands in Zone I and all islands in Zones II - III;

(g) effect of wind in uprooting, snapping off and decapitating trees, especially coconuts, and defoliating mangrove;

(h) effect of wind-driven rain and sea-water.

To some extent these factors are affected by local physiographic and vegetational conditions. Thus, beaches covered by dense vegetation such as Cordia-Bursera thicket are more resistant to erosion than bare beaches: deposition occurs round the margins but most of the thicket remains in the position of growth. Several examples have been noted. Further, the larger the cay, and the further from its shores, the less the damage to vegetation, except in the case of coconuts, which are highly susceptible to wind damage. The probability of catastrophic physiographic damage and hence of vegetation destruction is greater the less dense the vegetation, the lower and smaller the cay, the higher the storm surge, and the greater the wave action.

Vegetation damage takes the following forms:

(a) uprooting, particularly of coconuts, taller trees such as Coccoloba, and shallow-rooted bushes;

(b) removal of branches and twigs, as in Cordia and Bursera;

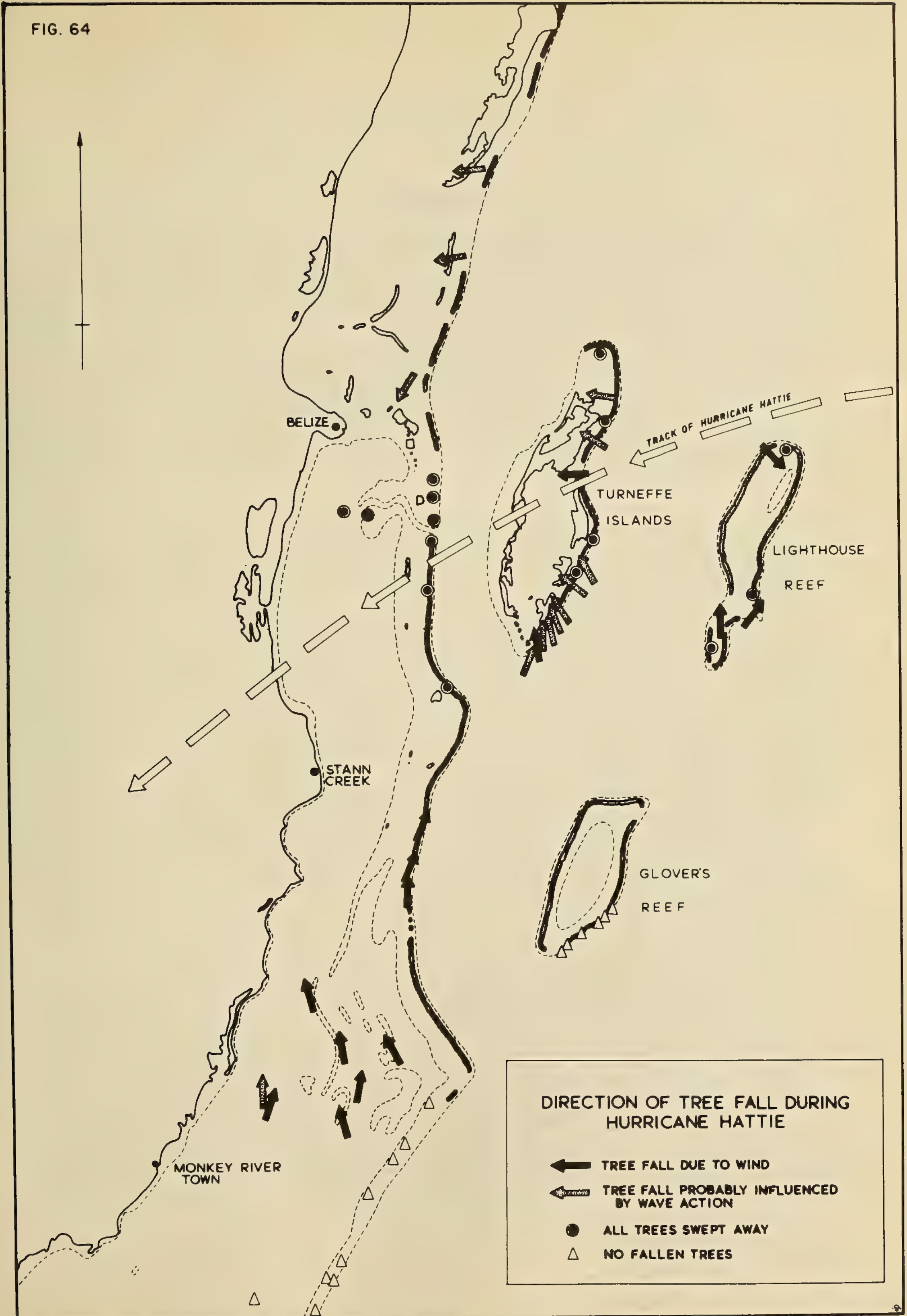
(c) removal of leaves, most obvious in Rhizophora, but seen also in Cordia, Bursera and many other plants;

(d) decapitation, confined to coconuts.

All these are superficial physical effects. No account can be given here of such matters as salt-spray soaking, increased groundwater salinity, and possible delayed mortality of injured trees, all of which would require detailed study. To sum up: the most striking vegetational changes associated with Hurricane Hattie were the widespread felling of coconut palms; the widespread defoliation of Rhizophora and other mangrove; and the destruction of beach and marginal vegetation, often through movement of the substrate, involving the complete disappearance over a 30-mile wide area of such characteristic cay species as Tournefortia gnaphalodes and Suriana maritima. These general conclusions relating damage at any point not only to species and vegetation type but to relative degree of wind, wave and surge action, correspond well with those of Fosberg (in Blumenstock, editor, 1961, 51-55) and Sauer (1962). Since

no attempt was made before or after the hurricane to make complete enumerations of species on any island, with the possible exception of Half Moon Cay, there is no point in including a detailed species-by-species discussion; for notes on individual species see the cay descriptions in preceding chapters. Fosberg (ibid. 54) noted that *Terminalia catappa* did not well resist wind damage, but in British Honduras it appeared to survive better than most trees. For a discussion of post-hurricane colonisation by plants, and the significance of differing effects on differing vegetation types in the wider question of cay evolution, see Chapter 11.

FIG. 64



TRACK OF HURRICANE HATTIE
BELIZE
D
TURNEFFE
ISLANDS
LIGHTHOUSE
REEF
STANN
CREEK
GLOVER'S
REEF
MONKEY RIVER
TOWN
DIRECTION OF TREE FALL DURING
HURRICANE HATTIE
TREE FALL DUE TO WIND
TREE FALL PROBABLY INFLUENCED
BY WAVE ACTION
ALL TREES SWEPT AWAY
NO FALLEN TREES

X. HUMAN AND ECONOMIC RESULTS OF THE HURRICANE

Settlement

Apart from the villages at Ambergris Cay (San Pedro) and Cay Caulker, both with a population of about 300, including a large proportion of Spanish-speakers, settlement on the cays is scattered and generally temporary. Before the hurricane there were fairly permanent settlements on St. George's Cay, a holiday centre; on a few widely scattered privately-owned islands (Tobacco Cay, South Water Cay, Carrie Bow Cay, Northeast Sapodilla Cay, Wild Cane Cay, Frenchman's Cay, on the barrier reef; Northern and Long Cays on Lighthouse Reef; Long and Southwest Cays on Glover's Reef); and on islands with lighthouses, on most of which Government maintained a keeper. Apart from the two villages and St. George's Cay, population of the cays probably did not exceed 150 persons at any time.

Hurricane effects on settlement were greatest in Zone I. On Sandbore Cay the lighthouse was destroyed, and this, Northern and Long Cays are no longer inhabited: only Half Moon Cay on this reef is still settled. On Turneffe, the Mauger Cay light stood but the island was made uninhabitable; hence in early 1962 the light was also out of action. The Cay Bokel light was destroyed, together with the island. Other settlements destroyed include the major coconut clearing centre at Calabash Cays; Soldier Cay and Cockroach Cay. Turneffe now has no permanent inhabitants, in contrast to the 7-8 small settlements before the hurricane. On the barrier reef, English Cay light stood, and though all houses were washed away the cay was re-occupied for navigational reasons almost immediately and houses were rebuilt. The Robinson Point light also stood: here the houses were also destroyed, but since the light is automatic the island has not been re-occupied. Bugle Cay light stood and the cay is still occupied. There was no change at Hunting Cay. Other settlements disappeared at Sergeant's, Spanish and Rendezvous Cays, and almost so at St. George's Cay. The barrier reef islands are now virtually uninhabited between Cay Caulker and Tobacco Cay. Forty-five persons lost their lives during the storm (Table I).

These remarks apply to fairly permanent settlements in houses. Much of the cay population, however, is literally a floating one: fishermen from coastal settlements visit the reefs for several days at a time, sheltering in their boats near islands at night. In some cases they construct palm-thatch huts for short stays, and exceptionally at Cay Glory built a number of houses on stilts on the shallow reef flat for use during the grouper season. This mainland-based visiting continues, particularly in the case of Caribs from Stann Creek and nearby villages, who continue to visit Weewee, South Rendezvous and other cays. The resumption of permanent settlement on the more devastated cays will presumably await their re-vegetation, which may take several years.

Economy

The most widespread economic resource on the cays before the hurricane was coconuts, which suffered heavy damage in Zones I - II, precisely those areas, close to Belize, where they had previously been most heavily exploited. Coconuts planted now could begin yielding after 1970; but it seems unlikely that either public or private capital will be free for coconut investment in view of demands on the mainland and the now-acknowledged vulnerability of the crop. A rehabilitation programme was put into operation following Hurricane Janet in 1955: "the futility (of this) was clearly demonstrated" after Hurricane Hattie, according to a report on agricultural damage by Wilson, Jolly and Chopin (1961). In 1962 coconuts in Belize and other coastal settlements were scarce and expensive, and nuts imported from Ruatan, Bay Islands, found a ready sale.

The complete destruction of boat-building yards at Robinson Point Cay and cessation of boat-building at Cay Caulker have been noted. Small-scale private boat-building continues at Half Moon Cay, but nowhere else. It seems unlikely that boat-building will be resumed on the islands on a commercial basis, and the industry will become even more localised in Belize. The only industries carried out on the cays now are small-scale: "corning" of fish for the Belize market, and domestic production of coconut oil for cooking.

Fauna

No systematic observations were made on land fauna. The pigs at Cay Bokel and Calabash Cays, Turneffe, disappeared during the storm, but those at Half Moon Cay took refuge in woodland and survived. Numbers of chickens disappeared on inhabited cays in Zone I. No observations were made on the survival of rats, *Iguana*, *Ctenosaura*, *Anolis* and other lizards on the cays on which they were found. Conditions after the hurricane were certainly ideal for rats, with much broken vegetation debris. Effects on birds seem to have been negligible. During the passage of the eye, Captain Eustace of the *Tactician* noted that "hundreds of birds, alive and dead, were clustered round the funnel, among them a few parrots, who were probably speechless"; these parrots must have been blown from the mainland by northwesterly winds, as parrots have only been seen on one island, Placencia Cay, near the mainland. Ospreys were widely nesting on damaged cays in early 1962, and *Fregata magnificens* in large numbers on Man-of-War Cay, central barrier reef lagoon. As noted in Chapter 7, the nesting period of the red footed booby, *Sula sula sula*, may have been delayed by several weeks as a result of the storm, though there may be an alternative explanation. After the hurricane one was impressed by the absence of birds from many damaged islands, especially *Pelicanus occidentalis* and *Fregata magnificens* from the heavily damaged islands of the northern barrier reef. It is possible that they moved southwards to the undamaged cays in Zone IV. In spite of the increase in area of standing water on many cays, no significant increase in the number of mosquitoes and other biting insects was noticed on any island.

XI. POST-HURRICANE ADJUSTMENTS AND PROSPECT

This final chapter briefly summarises changes in physiography and vegetation between Hurricane Hattie, 30-31 October, 1961, and the time of the re-survey 4-7 months later, notes probable future adjustments in the light of experience at Jaluit Atoll, Marshall Islands, and comments briefly on the ecological implications of the spread of coconuts into this reef area in post-Columbian time and the possible change in dominant hurricane effects which has resulted from it.

Topography

Destruction of the reef in Zones I - II removed an effective baffle which had previously limited wave activity on cay shores. Now waves suffer less bottom retardation at the reef edge, and larger waves reach cay shores. Several fishermen commented on this, which has resulted in a general steepening of cay shores and increasing roughness of anchorages. At the same time, reef destruction has led to the supply of increasing amounts of debris, now predominantly shingle and rubble, but ultimately as this is comminuted, of sand-size material also. This accounts for the rapid regrowth of temporary spits, as at English Cay, and the appearance of unvegetated sandbores, either where no cays had previously been seen (Jack's Cay and the small sandbore north of Goff's Cay) or where cays had long since disappeared (Slasher Sandbore). Where cays had disappeared during the hurricane, construction of embryonic sand cays which do not yet reach the surface has begun, as at Paunch Cay (built of shingle) and Cay Glory (built of sand). Shallow channels cut in cays at water level are in places filling up (northern channel at Sandbore Cay), though at St. George's Cay rapid tidal currents appear sufficient to keep at least four of the channels permanently open. The combined effect of increased wave action, increased debris supply and apparently increased sedimentation will presumably come to an end with the regrowth of reef corals and a return to pre-hurricane conditions. Complete recovery in the more devastated areas may take two decades or more (cf. Stephenson, Endean and Bennett, 1958).

Conversely, as at Jaluit, there is some evidence that constructional shingle features on reef-flats are unstable structures, at least on windward shores. In 1962 shingle ridges round some cays were being destroyed by the flushing out of sand and fine shingle, leaving a lag of coarser rubble. At Jaluit, over a period of three years, large reef-flat ridges on windward shores were pushed toward the island, leaving low rubble tracts or even bare reef flat, though leeward ridges suffered little change (Blumenstock, Fosberg and Johnson, 1961, 619). Topographic features least liable to change are depositional sand and shingle forms above the reach of wave action: these include ridges and carpets of sand and shingle piled on the old cay surface up to heights of 10 feet above sea level. Material in these ridges, which are being colonised by vegetation, may be broken down by weathering, but only further storm action can remove them as topographic features. Scour holes on cay surfaces are liable to slow filling with vegetation debris and wind-blown sand. Presumably areas where surface sand and soil have been completely stripped will also be recolonised by plants, and new soil formed over a period of years.

Vegetation

The main vegetation changes since the hurricane have been the colonisation of fresh sand and shingle areas by plants. On the completely devastated island of the northern barrier reef the chief coloniser was undoubtedly Portulaca oleracea, followed by Euphorbia mesembrianthemifolia and Sesuvium portulacastrum. Other colonisers include Cyperus planifolius, Fimbristylis cymosa, Ipomoea pes-caprae and Cakile lanceolata. Elsewhere in Zone I Portulaca was much less important, and on still-vegetated islands fresh sand carpets were being rapidly colonised by Ipomoea and Sesuvium, rather than Portulaca. Several islands, chiefly on the atolls, showed a considerable increase in Cenchrus, which had previously been kept in check by human interference. Following the destruction of the coconut canopy at Half Moon Cay, Wedelia trilobata seemed less widespread. In spite of the complete destruction during the storm of Tournefortia in Zones I - II, small seedlings were sprouting on most devastated islands in 1962, and may survive to maturity.

Recent spread of coconuts and changing hurricane effects

The great destruction of coconuts and lack of incentive to clear the debris and replant may possibly lead to some reversion to natural conditions on the cays. There is in fact considerable evidence that heaviest devastation on cays occurred precisely where human interference with natural vegetation and clearing for coconuts had progressed furthest. Many examples are given in this report of adjacent islands or even sections of islands where deposition occurred in thickly vegetated areas and erosion in sections cleared for coconuts or houses. If now the coconuts are not replanted, and the cays are allowed or even encouraged to develop a cover of Cordia, Bursera, Thrinax and dense shrubby undergrowth, then in future hurricanes, part at least of the vegetation cover may survive in the position of growth and form a nucleus for sand and shingle deposition, as at Half Moon, Cockroach II and elsewhere in 1961. In this way hurricanes might augment rather than decrease or even destroy reef islands. Complete clearance for coconuts and houses, particularly on seaward shores, as had taken place before 1961 at St. George's, Sergeant's and Rendezvous Cays, is an open invitation to catastrophic damage, and since it is no longer possible to regard hurricanes on this coast as very infrequent phenomena (cf. Appendix 1), the destruction of land, vegetation, property and life under such circumstances is only a matter of time. Cay owners and inhabitants, therefore, must choose between immediate amenity and long-term stability.

In this perspective, it seems at least probable that the known diminution in numbers of reef islands in historic time, as shown by the early charts of Speer and Jeffreys, and particularly by the detailed 1830 survey of Owen, has resulted largely from the increased destructive tendencies of hurricanes since the introduction and spread of the coconut by man in post-Columbian times, and specifically since about 1800. In their natural states, cays, to survive at all, must represent a delicate balance between forces of accretion and forces of degradation (Spender, 1937, 141): they must be in a state of dynamic equilibrium with their environment. In this

equilibrium, vegetation, stabilising and protecting the cay, must play a major part. The catastrophic changes brought about by Hattie and other recent hurricanes are largely the result of the disturbance of this natural equilibrium by clearing of the original vegetation. Thus, under present vegetation conditions, steep high shingle ridges are relict historical features dating from dense-vegetation days: such ridges today can only be built on those cays with a dense vegetation cover. Reef islands themselves are rapidly becoming transitory features.

Destruction of reef islands has been noted on a world wide scale by Stanley Gardiner, Kuenen and others. This interpretation, of increased efficiency of storm erosion and decrease in aggradation following clearing of natural vegetation, thus provides a key, more immediate than that of eustatic fluctuations of sea-level, not only to the great decrease in numbers of cays in historic time, but to the absence of islands in location where one would expect islands to form. Steers has noted that the difficulty in explaining the growth of cays is not so much to account for their formation but for their frequent absence, and that same dilemma has been noted in British Honduras (Stoddart, 1962a, 164). Hurricane action, following vegetational disturbance, may provide the key to this and other problems: man, not nature, appears as the culprit.

Conclusion

Hurricane Hattie presented an excellent opportunity to study hurricane action on reefs by comparison of "before and after" maps. For the same reason it would be of great interest to pursue this investigation, as at Jaluit, by a further re-survey in 1965. Changes in vegetation and adjustments to hurricane constructional and degradational features would form the theme of such a re-survey, which might well throw light on some of the admittedly speculative ideas put forward in this final chapter.

In 1962 one's main conclusion is that, terrifying as the hurricane was, its results were less catastrophic than might have been expected (even small sand cays escaped destruction), and that they would have been even less - and probably dominantly aggradational rather than destructional - had it not been for human interference with the cay environment. It is even questionable whether in the long-term view hurricanes should be considered as unusual and catastrophic events. Wolman and Miller's (1960) view, that it is the events of medium magnitude occurring every two or three years, which have the greatest geomorphologic significance, is based mainly on river studies and need not necessarily apply to coastal features. Let Charles Darwin have the last word. He, too, was impressed by the resistance of islands to the ocean waves at Cocos-Keeling: "Let the hurricane tear up its thousand huge fragments", he wrote in his Journal, "yet what will that tell against the accumulated labour of myriads of architects at work night and day, month after month?" (1839, 548).

XII. APPENDICES

1. Early British Honduras Hurricanes and their Effects

This appendix lists the major British Honduras hurricanes which have been recorded since 1787. Sources include the lists of West Indian hurricanes by Poey (1855, 1865), standard texts on hurricanes, especially Tannehill (1938), and studies of British Honduran history by Metzgen (1925), Burdon (1931-35), and Anderson (1958). The information in these works on earlier storms largely derives from the issues of the Honduras Almanack for 1829, 1830, 1832 and 1836. Other sources are indicated in the list. Efforts were made to obtain contemporary newspaper accounts for the period 1830-1900, but without success. The relevant periods are not covered by the Bancroft Library collection in California, and I have not been able to discover any other archive of early British Honduras newspapers. Newspaper accounts of storms in the period 1940-1960 were obtained from the holdings of the Jubilee Library, Baron Bliss Institute, Belize.

List of Hurricanes

1787, September 2nd. This is the first major hurricane on record. According to the Honduras Almanack (1829, 52), "This morning at 3 o'clock a hurricane came on which desolated the Settlement exceedingly, destroyed every home on it, but one; and considerable property; a number of lives were lost on this occasion, and many of the public papers. The shipping of the country went all ashore and were lost." Captain Allen adds that "a hurricane in 1787 caused the sea to rise at the entrance of the Belize River 7 or 8 feet, so as to overflow and destroy nearly the whole town. Great numbers of people were drowned" (1841, 83). Mr Lesley of the Bliss Institute kindly gave me the reference to a letter written by Major Richard Hoare to Admiral Alan Gardiner, dated St. George's Key, October 7, 1787, which gives an eyewitness account of the storm (Public Record Office, Admiralty Papers, i/243). Between 4 a.m. and 6 a.m. the wind blew at gale force, increasing to hurricane force at 8 a.m. and veering to south-east. By 10 a.m. the wind was still at hurricane force but was easterly. At about this time the low-lying areas were flooded by a wall of water 5-6 feet high. By 1 a.m. both the wind and the water had subsided. This hurricane was clearly comparable in intensity to Hurricane Hattie. For other brief references, see Nautical Magazine, 1848, 397, 453, 524.

1813, August 1st. Hurricane at Belize (on August 2nd according to Honduras Almanacks of 1826 and 1830). Smith refers to this storm as stripping leaves from the trees (1842, 732).

1813, August 25th. Hurricane, reference Nautical Magazine, 1842, 732. No details.

1827, August 19th. Hurricane at Belize; St. George's Cay flooded on August 20th (Almanack, 1829, 63). The storm "drove all the ships on shore at Belize" (Smith, 1842, 732).

1831, June 27th. Probably a minor hurricane, between Belize and Chetumal (Tannehill, 1938, 152), which also defoliated trees (Smith, 1842, 732).

1864, August 31st. Hurricane at Belize. The eye passed over the town itself and the sea rose 5 feet, causing widespread flooding (Tannehill, 1938, 236).

1893, June 6th. Severe damage done by a storm at Belize and in the southern districts (Metzgen, 1925, 20).

1902, June 20th. A minor hurricane in the Belize area (Tannehill, 1938, 164).

1915, October 15th. "Damage done by hurricane" (Metzgen, 1925, 21).

1916, September 1st. Minor hurricane in the Chetumal area (Tannehill, 1938, 183).

1918, August 25th. Minor hurricane in the Punta Gorda area.

1920, October 16th. "Hurricane struck northern part of the Colony, doing considerable damage. The sea at Corozal and Payo Obispo receded for several miles" (Metzgen, 1925, 28).

1931, September 10th. This hurricane was undoubtedly one of the worst in recent history, though only popular accounts exist (Cain, 1933; Burdon, 1932). The first storm warning was received on September 8th. At dawn on September 10th light rain was falling, with heavier showers at intervals; by 9.30 a.m. the wind was estimated at 36 mph. It continued to increase during the morning from the north-west, until 1.15 p.m., when it was estimated at 60 mph, with pressure 28.10 inches. Between 1.35 and 2 p.m. there was a lull and the wind dropped. At 2.05 the wind returned suddenly from the north, according to Cain, with a velocity of 60 mph. It continued to increase to 72 mph at 2.15 p.m.; 96 mph at 2.30; 120 mph at 2.35; and 132 mph between 2.50 and 3 p.m. Buildings began to collapse shortly after 2.15 p.m. After 3 p.m. the wind began to fall rapidly, and about a quarter to four shifted round to the south-west. The town was flooded by a storm surge 5-15 feet high. Minimum reported pressure was 27.6 inches. Several hundred people were killed, though Cain's estimate of 2500 was probably exaggerated.

1934, June 5th and 8th. According to Tannehill (1938, 212-213), a tropical storm crossed the British Honduras coast north of Belize on June 5th, moved into Peten, swung south into the Montagu lowlands, cut into the Gulf of Honduras near Puerto Barrios, and then travelled north along the barrier reef, again passing close to Belize on June 8th.

1942, November 8th. Twenty people were killed during a hurricane at Corozal.

1945, August 31st. A small hurricane brought rough seas and high tides during the afternoon; 4 persons were drowned at Calabash Cays.

highest winds were about 60 mph, and lowest reported pressure 29.23 inches, according to local press reports. This was one of the first hurricanes for which a series of advisories was received in Belize, but none were delivered to the authorities until September 3rd. As a result, a number of hurricane regulations were drawn up in time for

<u>1945</u>, October 4th. On October 3rd notice was received of a hurricane moving toward Belize at a speed of 7 knots, with winds of 85 mph over a 30-mile radius, and very rough seas. At 10.45 a.m., October 4th, it struck the Punta Gorda area, destroying 80% of the houses in that town and 70% of the houses in Monkey River. At Monkey River hurricane force north-westerly winds were blowing as early as 5.30 a.m. At 7.15 a.m. they backed to north, becoming more violent, and the sea level began to rise. By 8.30 the winds were north-easterly, and the water still rising. At 9.45 the winds reached a peak of violence as severe as at 7.15 a.m., and then began to abate. By 11.30 the hurricane has clearly passed, but Monkey River town was still covered with 18 inches of water. There was no lull at this place, but a 5 minute lull was observed at Erkenee's Point, and one of half-and-hour at Snake Cay and Punta Negra. According to the <u>Daily Clarion</u> of 6th October, Snake Cay was badly damaged.

<u>1955</u>, September 27th. Hurricane Janet largely destroyed Corozal and Chetumal. This has been described as "one of the fiercest hurricanes in history" (Dunn and Miller, 1960, 7; see 1-7, 74). Minimum recorded pressure at Chetumal, Quintana Roo, as the eye passed over was 27.00 inches, and wind speeds were well in excess of 120 mph; the Chetumal anemometer ceased recording at 150 mph. Damage estimated at £1 m.* was caused at Corozal in British Honduras. For a fuller account of this storm, see the U.S. Weather Bureau advisories, and Pagney (1957). It passed to the north of the British Honduras cays.

<u>1960</u>, July 15th. HurricaneAbby, a minor hurricane, struck Mango Creek, causing some shoreline readjustment and felling of coconut trees at Tobacco Cay. For details, see advisories.

<u>1961</u>, July 24th. Hurricane Anna, another minor storm, crossed the coast between Monkey River and Placencia during the early hours of the morning. The writer was at sea near Monkey River at the time, and visited the coastline that day. A number of trees were down at Placencia, which had been flooded. A carpet of fresh sand had been deposited on the north-east shore, over-lying uneroded grassland. Houses had suffered minor damage. Trees were also felled at Buttonwood Cay and at a nearby island near Gladden Spit. For meteorological details, see advisories.

<u>1961</u>, October 31st. Hurricane Hattie.

<u>Frequency of hurricanes</u>

These recorded hurricanes (there is no doubt that at least in the early period there were others not sufficiently severe to be noted) occurred in the following months:

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* $ 2,800,000.

June	July	August	September	October	November
4	2	5	4	4	1

Between 1830 and 1900 there were only 3 recorded storms, one of great violence compared with fourteen hurricanes in the slightly shorter period 1900-1962. These 14 storms included the very violent hurricanes of 1931, 1945, 1955 and 1961. Cry and Haggard (1962) have shown that the daily frequency of tropical storms and hurricanes in the North Atlantic area, 1901-1960, is greatest in August, September and October, reaching a peak in the first two weeks of September, and a secondary maximum in the middle of October. There are considerable differences in distribution of storms in different areas. Thus for the Atlantic coast of the United States there is no marked frequency maximum between June and October, whereas for the Atlantic Ocean south of 20°N and east of 55°W there is a very pronounced maximum in late August and September. In the western Caribbean, delimited by the Central American mainland between Cabo Catoche (Yucatan) and the Paraguana Peninsula (Venezuela), Haiti and Cuba, there is a preliminary maximum in June, followed by a quiet period in July, beginning to increase slowly in August and September, and building up to a maximum in mid-October (Cry and Haggard, 1962, 343). 63% of the 110 tropical cyclones and 70% of the 57 hurricanes have begun in this area between September 15th and November 15th.

British Honduras can thus reasonably expect at least one hurricane a decade, probably more, and more violent catastrophic storms at least once every thirty years, perhaps more often. These storms are most likely to occur in September or October. Placed against the background of the history of the cays, which presumably came into existence soon after the sea reached its present level, hurricanes are thus frequent phenomena.

2. Some Maya Pottery from Grand Bogue Point, Turneffe Islands, British Honduras

Euan W. MacKie
Hunterian Museum, University of Glasgow

Some thirty fragments of more or less weathered pottery were received for examination, all of which had been collected by Mr Stoddart from the surface at Grand Bogue Point (Figure 54). Although the majority of the pieces do not have precise parallels with material excavated from sites in the Cayo District of British Honduras, the area with which this writer has first-hand knowledge, there seem to be sufficient general similarities with other sites in the territory to permit an approximate placement of the collection in the overall ceramic sequence of this part of Maya Central America.

Two main classes of pottery are present (Figure 65): sherds with traces of a bright red slip, usually termed Red ware; and plain sherds. Some of these last may have lost their slip through weathering, but most seem to be fragments of plain, unslipped vessels. Red ware vessel types include shouldered dishes, (o) and (p); storage jars, (g) (h) (i) (q) (r); a bowl with carved decoration, (l); a probable lid, (n); a sherd with incised decoration, (k); a large fragment of a ring-base, (j); a slab-foot with incised decoration, (s); and a fragment of a perforated spout or hollow handle, (m). Plain vessels are mostly large storage jars, (a) (b) (c) (d) and (f), but include one (e) which might from its size be a weathered example of the black slipped storage jars commonly found at the Cayo District sites and termed fugitive black ware. Three fragments of solid pottery cylinders with one end rounded were present; these are usually assumed to be parts of incense burners (Borhegyi, 1959). Two struck flakes of flint were also included with the collection.

In the assessment of the chronological position of these sherds in the ancient Maya ceramic sequences the absence of polychrome painted pottery may be significant. The ultimate phase at such Classic period ceremonial sites as Uaxactun, Xunantunich and San José is distinguished by a marked decline in polychrome wares; however, recent work at the second site has demonstrated that a poor wooden hut may entirely lack painted wares at a time when they were abundant in the nearby ceremonial site (MacKie, in litt.) The absence of painted sherds may also indicate a pre-Classic or Early Classic age but the other indications listed below combine to favour a much later date.

The Red ware storage jars (h) and (r) have a profile with a sharp angle inside the neck which is closely similar to unslipped jars found in phases IV and V at San José (Thompson, 1939, Figures 66 and 76). Red ware vessels with ring-bases occur at San José from phase II onwards, but the forms most similar to (j), with a high almost vertical ring, occur in phases IV and V (Thompson, 1939, Figures 68 and 78). The two Red ware shouldered dishes (o) and (p) each exhibit a groove and a row of impressions along the shoulder, features quite well paralleled at San José in phases IV and V (Thompson, 1939, Figures

68, 69 and 80) and at Xunantunich in phases IIIb and IV (Thompson, 1942, Figure 47; MacKie, in litt.). The plain jar (c) has its counterparts at Xunantunich in phase IV (Thompson, 1942, Figure 6, s and t).

The carved Red ware bowl (l) and the Red ware sherd with incised decoration (k) also have general analogies in the Late Classic phases at San José and Xunantunich. Carved Red ware occurs at San José in phases IV and V (Thompson 1939, Figures 67 and 85) and at Xunantunich in phase IV (MacKie, in litt.), in which phase also appears some incised Red ware (Thompson, 1942, Figure 48). The closest parallel for the very large Red ware jar (q) seems to occur somewhat earlier, at San José in phases III and III/IV (Thompson,1939, Figure 59); and the slab-foot (s) also has generalised analogues in an earlier phase of the Late Classic, in periods IIIa and IIIb at Xunantunich (Thompson, 1942, Figures 15, 24, and 41; MacKie, in litt.).

The solid pottery rods (t), probably parts of incense burners (Borhegyi, 1959), are known to have been used for many centuries (Borhegyi, 1956), but they appear to increase in numbers in British Honduras ceremonial sites in Late Classic times (MacKie, in litt.).

Thus the majority of the analogies drawn between the Grand Bogue sherds and material from ceremonial sites elsewhere in British Honduras are consistent with their belonging to a stage in Late Classic or early post-Classic times, corresponding to phases IIIb and IV at Xunantunich and IV and V at San José. It might be expected that remains from areas peripheral to the nearest main centres of Maya Classic culture, Guatemala and western British Honduras, should belong to the period of maximum population expansion, and excavations at the ceremonial sites of Xunantunich and San José, and the settlement site at Barton Ramie on the Belize River (Thompson, 1939, 1942; MacKie, in litt.; Willey, Bullard and Glass, 1955) strongly suggest that the Maya population in the British Honduras area was at its maximum in Late Classic times.

It is now possible to give these later phases absolute dates in years with some accuracy. The extensive excavations at Uaxactun in Guatemala have provided a long ceramic sequence which can be tied to many of the dated stelae there, and which can also be correlated with the sequences at sites in British Honduras. Ceramic analogies suggest that the two final phases at San José, IV and V, correspond approximately to the last two at Xunantunich, IIIb and IV, and that both are roughly coeval with the last two phases at Uaxactun, Tepeu 2 and 3 (Thompson, 1942; MacKie, 1961,220). R. E. Smith (1955, 106) places Tepeu 2 and 3 in the 8th and 9th Centuries A. D. and the Grand Bogue sherds ought to be of similar age. However, Maya activity on some of the cays of British Honduras undoubtedly continued later, judging by the fine Plumbate pottery found on Wild Cane Cay (MacKie, in litt.). This widely traded pottery has been dated to the 11th and 12th centuries A. D. (Shepard, 1948, 115).

Description of the sherds (diameters indicated on Figure 65):

(a) plain light brown and orange, sand tempered; no trace of slip; horizontal striations inside and out.

(b) dark grey clay, light brown surfaces; horizontal striations; no trace of slip; sand tempered.

(c) friable light brown clay, sand tempered; horizontal striations on external surface; no trace of slip.

(d) light grey clay, and light brown mottled surfaces; sand tempered with horizontal striations; no trace of slip.

(e) fine light yellow-brown clay with orange core; sand tempered; no trace of slip.

(f) bright orange clay, darker mottled areas on surface; sand tempered; marked horizontal striations on interior; no trace of slip.

(g) light grey clay, cream surfaces; sand tempered; traces of bright red or orange slip; two faint horizontal grooves on exterior just below angle of rim.

(h) light grey clay, light brown surfaces; brownish slip inside and out, probably red originally; sand tempered; horizontal striations.

(i) dark grey clay, light brown surfaces; red slip; sand tempered; horizontal striations.

(j) ring-base; dark grey clay, cream surfaces, traces of red slip; sand tempered; horizontal striations underneath.

(k) light grey clay, light orange surfaces; red slip on exterior; sand tempered; incised decoration apparently done after application of slip, but weathered; part of a carinated vessel; sand tempered.

(l) light grey clay, cream surfaces; traces of red slip; sand tempered; decoration incised and carved out, probably after application of slip, but too weathered to be sure.

(m) light orange clay, sand tempered; red slip on all visible surfaces except inside tube; small hole, smooth-sided and probably made before firing.

(n) lid (?) Grey clay, light brown surfaces; sand tempered; ring at top applied separately and smoothed down; red slip on under surface, upper surface severly weathered; horizontal striations on under surface.

(o) light grey clay, orange surfaces; sand tempered; traces of red slip on both faces; upper groove at least made before application of slip.

(p) grey clay, light brown surfaces; slip on both faces, darker red than on (o); sand tempered; row of impressed marks at shoulder made with corner of instrument with rectangular end; hole drilled through, presumably for a repair.

(q) grey clay, light brown surfaces; sand tempered; horizontal striations; traces of dark red slip on exterior.

(r) similar to (h).

(s) light brown clay; faint traces of dark red slip on outer surface, more clearly on upper surface; tempered with many minute fragments of white material, possibly shells.

(t) light brown clay; sand tempered; no trace of slip.

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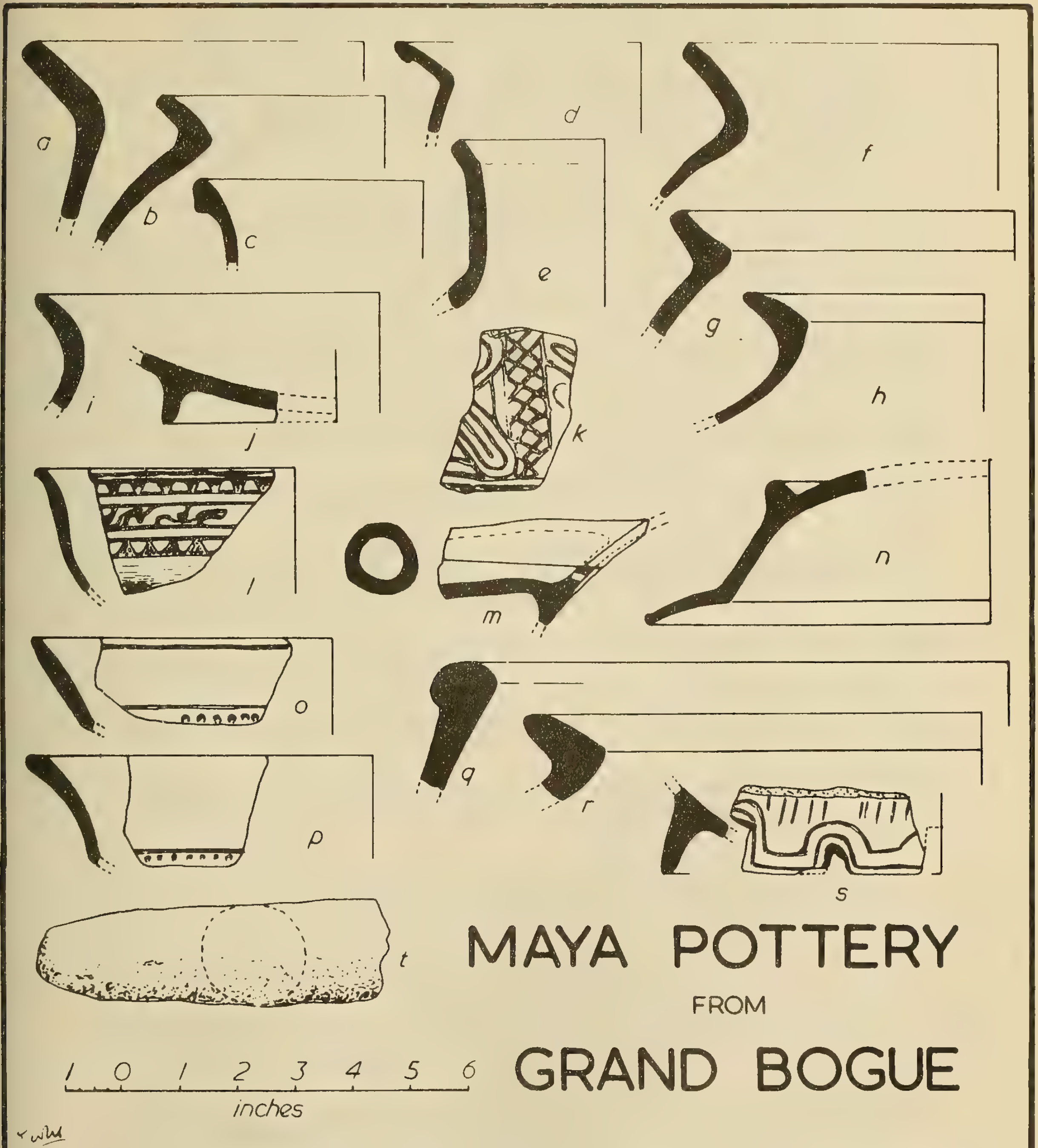
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MAYA POTTERY
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FIG. 65

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Some aspects of the meteorology of the tropical Pacific viewed from an atoll

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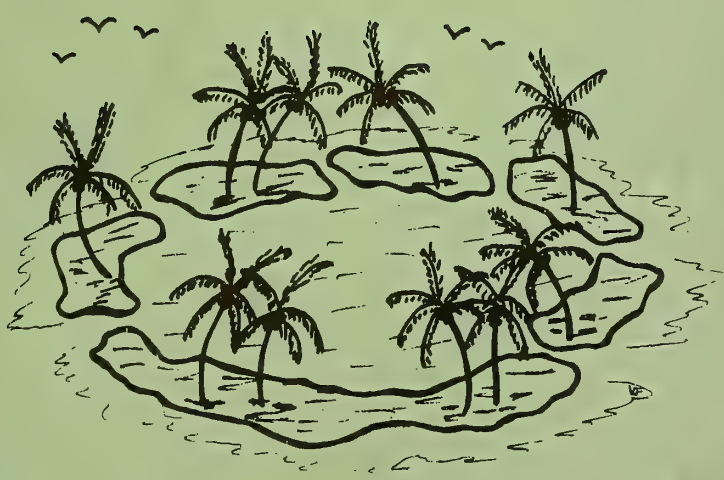

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It is of interest to note, historically, that much of the fundamental information on atolls of the Pacific was gathered by the U.S. Navy's South Pacific Exploring Expedition, over one hundred years ago, under the command of Captain Charles Wilkes. The continuing nature of such scientific interest by the Navy is shown by the support for the Pacific Science Board's research programs during the past fifteen years.

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CONTENTS

LIST OF TABLES AND FIGURES

ABSTRACT

A detailed climatological study of surface and upper-air data from Eniwetok Atoll was carried out in order to throw light upon various tropical oceanic problems including island influence, diurnal variations, and the nature of synoptic disturbances. Among results of the analysis are: 1) the atoll influence upon cloud or precipitation over the atoll itself is hardly detectable and probably insignificant; 2) the diurnal variation of the surface wind is almost exclusively the result of world-wide, atmospheric tidal motions, except for a possible speed increase of less than 0.1 kt near mid-day; 3) low cloudiness shows a diurnal variation whose range is less than 4% of total sky with maximum cover at 0700 local time; 4) precipitation occurrence shows a distinct early morning maximum; 5) in synoptic disturbances affecting the region, equatorward flow gives rise to a slight tendency for better than normal weather while poleward flow is associated with markedly wetter weather; 6) disturbances which make themselves felt primarily in the wind speed field appear to contribute significantly to bad weather periods at Eniwetok.

The problem of diurnal rainfall variation is elaborated by inclusion of data from a weather ship and several other atoll stations. Various hypotheses are examined and it is concluded that the variation in shower frequency is most likely the result of cumulative stabilization of the cloud layer by absorption of solar energy in the cloud tops by day. The variation in low cloud cover is felt to be due primarily to a diurnal variation in sensible heat transfer across the air-sea interface.

Introduction

The renaissance which tropical meteorology has experienced since about 1940 has been channelled quite understandably in the direction of a better understanding and prediction of the life cycle of tropical cyclones. In spite of the tremendous significance of improvement in this area, there are meteorologists who will remind us that the important tropical problems demanding solution are not limited to the circulation of the tropical cyclone. In this group of meteorologists are the forecasters in those areas generally free from these destructive storms who must face the vexing problems provided by the "undisturbed" or weakly disturbed tropical atmosphere. Also there are those who feel that the improvement in our understanding and prediction of the tropical cyclone will be, or indeed may already be, stunted by the deficit of knowledge of the smaller scale or more normal processes of the tropical atmosphere. Finally, the student of the general circulation of the global atmosphere will remind us that the heat and moisture fed into the tropical atmosphere plays the role of prime mover for the large scale motion systems of ocean and air. Most of this driving energy and its day to day variations must be provided through processes apart from tropical cyclones.

The tropical latitudes are largely oceanic. The proper framework for building an understanding of the tropical atmosphere must rest upon a precise description of ocean-atmosphere interaction processes and accurate measurements of the atmosphere over the sea. But where does one gather such information? There have been no weather ships stationed

deep within the tropics, and oceanographic expeditions rarely stay in one place long enough to provide definitive description.

Islands are plentiful only in restricted regions of the tropical oceans, yet these provide us with stable observing platforms which have contributed much of our knowledge of tropical maritime weather. However, the tropical atmosphere is frequently in such delicate balance with the sea surface that even a rather small island might conceivably leave an indelible imprint upon local weather and our picture of the low level atmosphere. Accounting for these local influences is generally far from a simple task. Furthermore, how can a rational understanding be conceived until one learns what the variations would be without the intrusion of a land mass?

The primary objective of this investigation has been to scrutinize the standard meteorological observations from a coral atoll to determine: 1) the extent to which such a tiny island disturbs its atmospheric environment; 2) the character of diurnal variations over the sea; 3) the contributions which a detailed climatological analysis of such records might be able to make on the question of the nature of low-level disturbances in the central tropical Pacific.

When problems such as these have been dealt with satisfactorily it should be possible to make more intelligent use of island and ship observations in the tropics. From the applied standpoint such information would be very helpful in building a proper frame of reference for the evaluation of orographic and heat source effects on tropical islands.

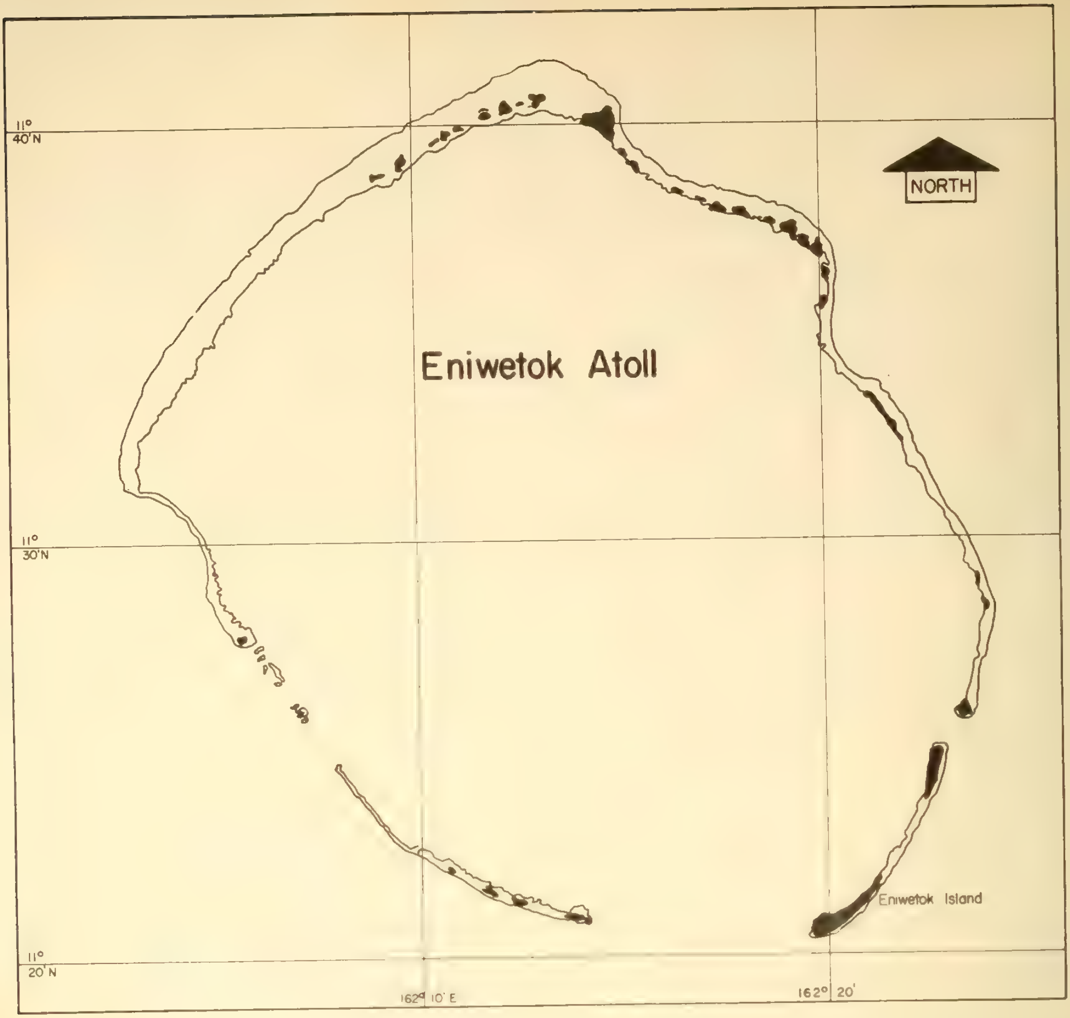
Part I: Eniwetok As an Observing Platform

It is, of course, improper to ask whether a small island has any effect on the overlying atmosphere. Even the smallest islet has some effect, even if the influence be limited to the lowest few centimeters of air. Furthermore one must not neglect the action of the sub-surface land mass as an obstacle to normal oceanic processes. This might alter the surface-water properties in the neighborhood of the island and transmit its influence to the atmosphere indirectly.

One must first select the variable and the location of its measurement and then ask whether the influence of the island makes a significant impression. Conjuring up experiments to answer such a question is an interesting pastime, but under the constraint of existing data the approaches are few and the answers are perhaps only suggestive.

Eniwetok atoll was selected for intensive study for several reasons. It is firstly representative of a moderate sized atoll far removed from other land and overlain by a persistent trade wind regime throughout the year. Secondly, the atoll has been the site of special intensive data collection on several occasions as the result of nuclear test programs in the area. Thirdly, the University of Hawaii has on file some 150,000 punched cards containing hourly surface observations, radiosonde and rawinsonde data for much of the period of record at Eniwetok. This file is a portion of the Pacific data library transferred to the University by the meteorological support arm of Joint Task Force Seven.

Eniwetok is an isolated atoll situated at the northwest edge of the Marshall Islands group. It is some 2500 statute miles west-southwest of



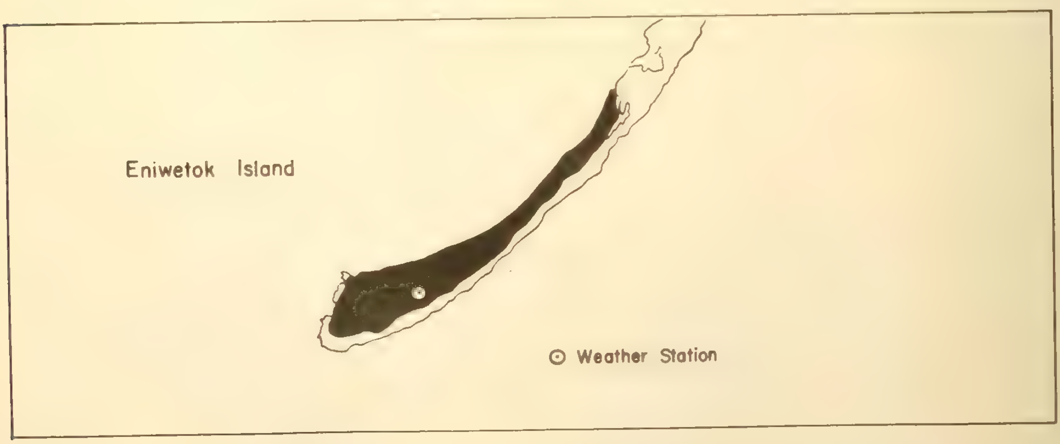


Fig 1. Outline map of Eniwetok Atoll. Dark areas depict dry land, clear outlines show outer margin of reef flats. Location of weather instruments is shown on enlarged chart of the main islet at bottom.

Honolulu at 11.4N, 162.3E. The atoll consists of a chain of about thirty small islets strung on coral reef around an oval lagoon 25 miles long by about 20 miles wide (Fig 1). Most of the islets are less than 13 ft high but some have coconut palms reaching to over 80 ft. The lagoon is quite deep, approximately 155 ft on the average. A detailed presentation of the geology and hydrography of the atoll is available in a report of the U. S. Geological Survey (Emery et al, 1954). A comprehensive summary of the topography, vegetation, and climate of Eniwetok is provided, along with original data from a brief, intensive microclimatic observational program, by Blumenstock and Rex (1960).

The only meteorological data of sufficient extent and homogeneity were collected near the main runway on Eniwetok Islet (Fig 1). It will be noted that this location is on the windward side of the atoll under prevailing east-northeast flow. The standard instruments are so situated that the air reaching them under typical trajectory probably traverses less than 400 meters of land surface.

With data from only one station on an atoll the evaluation of disturbances resulting from the atoll is difficult at best. An obvious approach is to determine the diurnal variation of various elements and to compare these with the expected trends resulting from the presence of a land surface. This will be done in the next section. Certainly the most important effects of the atoll would be the result of the contrasting heat transfer processes of land versus water and these should be exemplified by diurnal curves.

This approach is not completely satisfactory since there may remain some systematic influence present both day and night. One might expect,

for example, a different surface friction regime over the islets to have some effect on low-level winds. Also the lagoon water temperature may well be maintained at a slightly higher value than that of the surrounding free ocean where free circulation is unimpeded. The temperature difference is probably slight in this case with a deep lagoon and considerable tidal and wave exchange through channels and over inter-tidal reefs. Some scanty data are available (Blumenstock and Rex, 1960) which indicate that the lagoon surface water is usually less than 1°F warmer than the nearby ocean in August. A heat source of this magnitude seems unlikely to make itself felt in the cloud and precipitation regime.

An attempt to throw some light on this latter problem was made by a study of weather variations associated with the state of the oceanic tide. The reasoning here was as follows. Atolls generally possess a large reef area which is essentially exposed at low tide but submerged at high tide. In the case of Eniwetok the total dry land at high tide is only 2.5 mi^2 while at low tide exposed land (and tidal pools) covers some 34 mi^2 (Emory <u>et al</u>, 1954). This fourteen-fold increase is the result of a mean diurnal tidal range of 3.9 ft. It is reasonable to expect that the magnitude of the atoll heat source would be significantly increased therefore during those days when the low tide coincides with the hour of maximum heating. In addition to the order of magnitude difference in exposed land area there would be more shallow water and less lagoon water exchange at low tide.

Following this reasoning, the U. S. Coast and Geodetic Survey Tide Tables were examined for cases of maximum or minimum tide occurrence between the hours of 1200 and 1330 LMT for Eniwetok. Such an event will

be referred to as either a "high tide day" or a "low tide day". The dates of occurrence as well as the height of the tide and its range during the previous six hours were recorded for the period of record, June 1949 to February 1959.

The hourly surface reports were then examined for these dates and data were recorded for 0700, 1000, and 1300 LMT. The recorded observations included values of temperature, dew-point, low cloud amount and precipitation occurrence.

The mean increases of temperature and dew-point from 0700 to 1300 hrs were computed on low tide days and on high tide days and these were compared. It was hoped that this procedure would tend to reduce the possibility that any difference between the two sets of days could be due to chance synoptic influences. It might be expected that on days when the tide reached a minimum near 1300 hrs that the temperature (and possibly the dew-point also) would show greater increase from early morning to 1300 hrs. The analysis in fact revealed no significant difference between low and high tide days. The temperatures and dew-points showed mean differences of less than 0.05°F as a result of tide change. This result is not unexpected, however, since the tidal variation will have only a slight effect on the length of air parcel trajectory from water's edge to thermometer shelter (see Fig 1). The total heat transfer between the parcel and the surface must be insignificantly different from low to high tide situations.

This should not be the case with low cloud cover and precipitation, however. These quantities might be expected to respond to the area

effect of the heat source and to integrate the exposed reef increments over a large part of the atoll.

The analysis of precipitation could not be made satisfactorily due to the nature of the data. There were no hourly precipitation amounts available, only occurrence versus non-occurrence. Furthermore, the latter had to be taken from hourly "Airways" observations which report weather only during a 3 minute segment of the hour. Thus, in dealing with a small sample of days, the element of chance observations plays too large a role to allow statistical significance.

The amount of sky covered by low cloud for this 3-minute period is reported in tenths of total sky. This variable was carefully analyzed. In order to further limit the chance that a few synoptic disturbances might approach the atoll in the forenoon and give a random increase to one or the other sets of "tide days", values were compared at 1300 and 1000 LMT on each day. With tidal maxima or minima occurring near 1300 hrs on these days, 1000 hrs should represent the tidal node and these data should thus have little dependence upon the direction of tidal change. Those who have examined tidal records, however, will realize that not all "high tides" or "low tides" correspond to a significant change in elevation of the sea surface. This diluting factor was reduced here by ranking the cases according to the magnitude of the tidal deviation and selecting the top one third of each set of tide days so ranked for further analysis.

The change in low cloudiness from 1000 to 1300 LMT was then recorded for low tide days and for high tide days and values averaged for each of the 12 months. The comparison by month appeared advisable because of the

possible existence of a seasonal trend in the background diurnal variation of low cloud cover. Table 1 summarizes the results of this analysis which utilizes data from June 1949 to December 1958. Entries are in tenths of sky cover.

TABLE 1

Influence of Oceanic Tide on Low Cloudiness

Month	High Tide N_h(13-10)	Low Tide N_h(13-10)	ΔN_h Col.1-Col.2	No. of Pairs
Jan	-0.33	-0.47	0.14	15
Feb	-0.67	-0.63	-0.04	15
Mar	0.70	-0.17	1.23	15
Apr	0.07	-0.17	0.24	15
May	-0.13	1.23	-1.36	15
June	0.87	-0.47	1.34	15
July	0.53	0.13	0.40	15
Aug	-0.53	-0.50	-0.03	15
Sept	0.67	-0.27	0.94	15
Oct	0.10	0.07	0.03	15
Nov	0.17	-0.03	0.20	15
Dec	-0.70	0.40	1.10	15
TOTAL	2.05	-1.24	4.15	180

With the exception of May the values seem to indicate more cloud cover during afternoons with a high tide, although the mean cloud increase (May included) is only 0.35 tenths of sky. The result is contrary to expectations. A two-tailed test of significance utilizing the Student's "t" distribution shows no cause to accept this result as significantly

different from zero at the 95% level of confidence (this is largely due to the adverse May value which survived a thorough rechecking). With the variance demonstrated in these data a difference as large as 0.35 might be expected about 14% of the time in similar samples from a population of differences whose real mean is zero.

The only conclusion to be drawn is that the analysis was unable to show that an order of magnitude change in the exposed land surface of this atoll had any effect upon low-level cloud cover. This result might be used to argue that the atoll itself has no influence on low clouds. In defense of proponents of the alternate hypothesis, however, it should be pointed out that less than half of the sky viewed from the observing station lies over the atoll and that much of the extensive reef area lies across the lagoon (Fig 1). Furthermore it will be observed that the lagoon itself covers an area (360 mi^2) which is an order of magnitude larger than the land exposed at low tide. However, lagoon waters certainly provide a relatively feeble heat source when compared to land near mid-day.

The conclusion reached here is compatible with reports from meteorologists who have resided on atolls, i.e. that there appears to be no preferential location by quadrant, for trade cumulus build-ups. On the other hand it runs counter to many stories that claim experienced polynesian navigators could distinguish the presence of tiny islands in the distance by virtue of the cloud distribution. It must be stressed here that the foregoing analysis could only hope to uncover a fairly sizable effect observable from the atoll itself. It is possible that the disturbance in cloud organization is felt primarily downstream from the atoll. Some evidence in favor of this conclusion is found in the study of diurnal rainfall variation on Majuro Atoll (page 35).

Part II: Diurnal Variations.

General comments.

The punched card deck available for Eniwetok consisted of hourly "Airways" reports for the period from June 1949 to February 1959. Several months in this period were incomplete, however. There were scattered periods when only 3-hourly observations were recorded and other periods when one or more elements of the reports were missing irregularly. In compiling diurnal variations from this data file using the IBM 650, care was taken to assure accuracy and homogeneity of record. The machine was programmed to make elementary consistency checks on the data and to exclude those days when more than one observation was missing. Monthly mean hourly values were then computed for each month for each of the following: sea level pressure, wind speed, zonal and meridional wind components, temperature, dew-point, wet bulb temperature, relative humidity, low cloud amount and occurrence of precipitation. Each monthly mean value represents at least 200 days or about 7 years of homogeneous data.

In order to further elucidate the character of the diurnal variations, harmonic analyses were performed on the monthly and annual mean hourly values of pressure, wind, temperature and humidity. The analysis was carried to four harmonics for each variable according to standard procedures (e.g. Panofsky and Brier, 1958). The values of these harmonic components for the annual means are presented in Table 2. The representation for the magnitude of the variable x at local mean solar time t_i (in hours) is given by:

$$x = \bar{x} + C_1 \cos\left[\frac{2\pi}{24}(t - t_1)\right] + C_2 \cos\left[\frac{2\pi}{12}(t - t_2)\right] + C_3 \cos\left[\frac{2\pi}{8}(t - t_3)\right]$$
$$+ C_4 \cos\left[\frac{2\pi}{6}(t - t_4)\right] + \text{H.H.} \quad \ldots\ldots\ldots\ldots \quad (1)$$

where $\bar{x}$ is the mean daily value of the variable, C_1 to C_4 are the amplitudes of the first to fourth harmonics respectively, t_1 to t_4 are the respective phase hours of each harmonic, and H.H. represents the contribution of the eight higher order harmonics which are needed for a complete representation. If the observed mean hourly values of x are plotted and compared with the plot of the single cosine curve given by the first harmonic in (1), the observed points will of course not all lie exactly on this curve. A measure of the contribution which each individual harmonic makes toward reconstructing the observed curve is given by forming the ratio of the variance of that harmonic curve to the variance of the mean diurnal curve. If this ratio is multiplied by 100 we have the percent of the observed variance which is "explained" by the given harmonic. This information is provided in the row headed "%V" in Table 2. The percent variance is additive so that when all 12 harmonics are utilized, $\Sigma\%V_i = 100\%$.

With all meteorological variables it is found that the diurnal and semi-diurnal harmonics together provide for most of the mean daily variation of the variable. Higher harmonics generally make increasingly smaller contributions and their physical significance become increasingly more questionable. They are more and more likely to be the reflection of random errors in the data.

TABLE 2

Annual Harmonic Components of Diurnal Variations of Pressure, Wind, Temperature and Humidity

	Sea Level Pressure	E Wind Component	N Wind Component	Air Temperature	Dew Point	Wet Bulb	Relative Humidity
c_1	0.39 mbs	0.10 kts	0.07 kts	2.42°F	0.51°F	1.01°F	4.6%
c_2	1.03	0.20	0.18	0.84	0.26	0.39	1.4
c_3	0.09	0.03	0.03	0.08	0.05	0.06	0.2
c_4	0.02	0.02	0.03	0.18	0.05	0.08	0.3
t_1	4.53 hrs	7.11 hrs	22.29 hrs	13.22 hrs	13.26 hrs	13.24 hrs	1.23 hrs
t_2	10.04	9.99	6.76	0.38	11.47	11.98	6.18
t_3	1.60	4.60	2.26	0.60	1.31	1.01	4.34
t_4	4.28	1.72	23.24	3.48	3.20	3.34	0.58
$\%V_1$	12.6%	19.1%	13.3%	88.7%	73.2%	86.1%	90.9%
$\%V_2$	86.6	73.4	78.5	10.5	19.9	12.9	8.4
$\%V_3$	0.6	1.2	1.6	0.1	0.6	0.3	0.1
$\%V_4$	0.04	0.7	1.5	0.5	0.8	0.6	0.5
TOTAL %V	99.9	94.4	94.9	99.8	99.5	99.9	99.9
ANNUAL MEAN	1009.96 mbs	12.65 kts	3.73 kts	81.96°F	74.46°F	76.54°F	78.45%

The phase hour, t_i, is to be interpreted as the first time on the 24 hour clock at which the i^{th} harmonic of that variable reaches a maximum. Oviously the i^{th} harmonic has i maxima and i minima over the 24-hour day. The hours are given in local mean solar time (LST minus 1.18 hrs). All susequent references to time in this report will be local mean time (LMT) unless otherwise noted.

Consideration of the significance of the harmonics in Table 2 will be included in the following discussions of the diurnal variations of individual meteorological elements.

Sea level pressure

Both the descriptive and theoretical aspects of the mean diurnal variation of atmospheric pressure have been studied extensively for nearly 200 years. The most recent survey of this problem is probably given by Siebert (1961). It was early recognized that these variations were of larger amplitude in the tropics and were more easily studied at these latitudes where synoptic pressure disturbances were generally small and infrequent. Still there exist some unanswered questions or at least some weak hypotheses concerning several facets of the surface pressure oscillations. The results of an analysis of the mean diurnal pressure variation are presented here in some detail partly as a data contribution to the general descriptive problem of atmospheric tides but also as supporting information for the following discussion of diurnal wind variations.

The semi-diurnal component of the atmospheric tides has received the most concentrated attention and its description has achieved the most

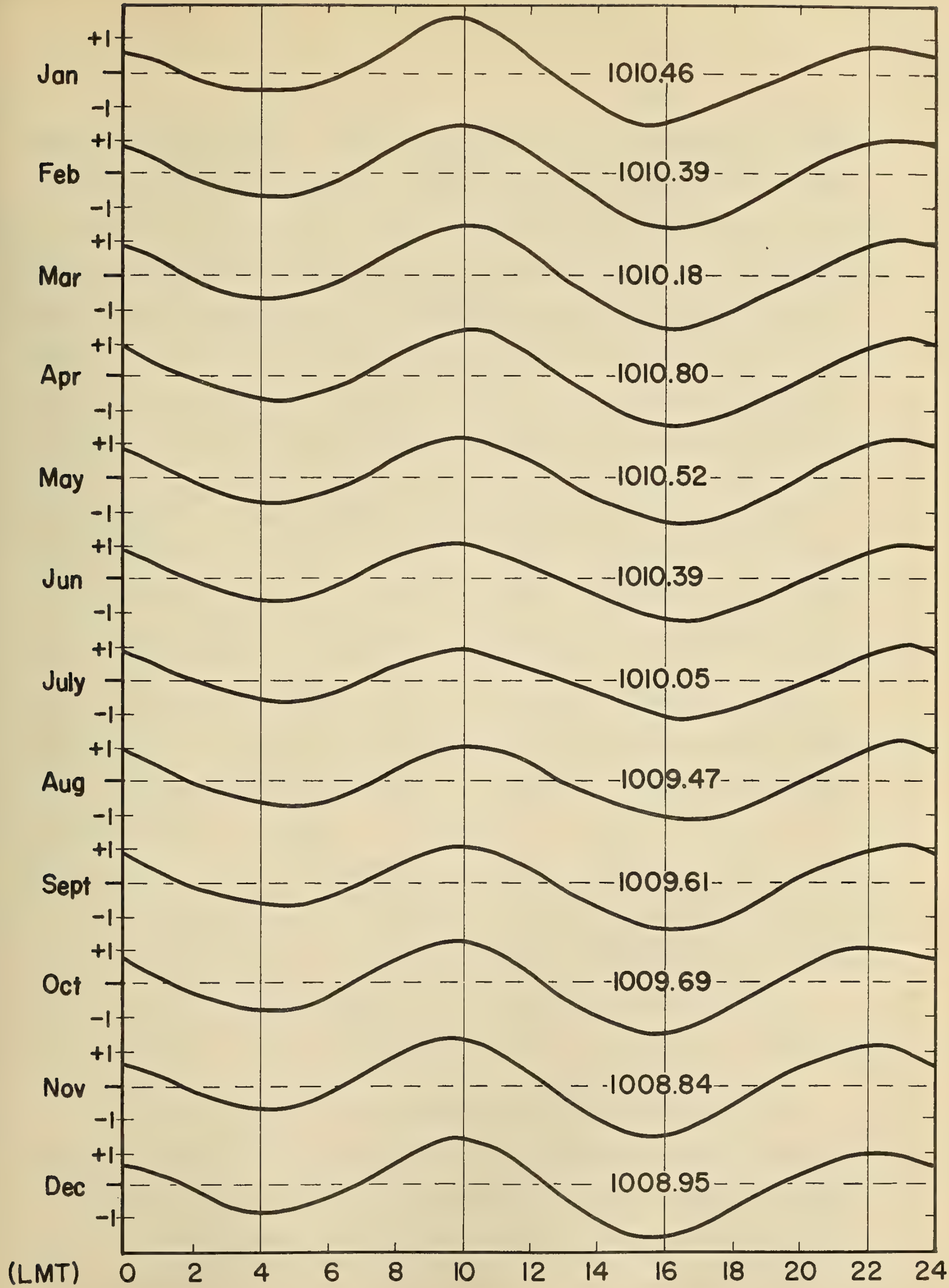


Fig 2. Mean monthly curves of diurnal variation of surface pressure at Eniwetok. Values are expressed as deviations from the monthly mean pressure in millibars. Time of day is local mean time.

universal agreement. The diurnal oscillation is consistently weaker, more susceptible to local influences (land-sea breeze, altitude, cloud cover, etc.), and less stable with respect to its seasonal fluctuations. Table 3 depicts the seasonal trend of the first three harmonic tidal components of pressure at Eniwetok, while Fig 2 presents the observed mean monthly curves.

TABLE 3

Monthly Mean 24-, 12-, and 8-hourly Pressure Oscillations.

	C_1(mbs)	t_1(hrs)	C_2(mbs)	t_2(hrs)	C_3(mbs)	t_3(hrs)
Jan	.45	5.19	1.08	9.88	.20	1.98
Feb	.47	5.11	1.12	10.10	.17	1.91
Mar	.51	5.27	1.13	10.13	.10	1.58
Apr	.49	5.27	1.10	10.14	.09	1.17
May	.36	4.71	1.02	10.16	.06	0.49
June	.36	4.47	.88	10.30	.07	7.88
July	.33	4.30	.86	10.46	.06	7.73
Aug	.33	3.65	.96	10.40	.04	0.78
Sept	.41	3.90	1.03	10.05	.05	1.01
Oct	.36	4.58	1.10	9.76	.11	1.89
Nov	.36	4.84	1.12	9.64	.14	1.94
Dec	.40	5.26	1.09	9.37	.17	2.13

The diurnal component of the atmospheric tides is a global phenomenon which is due primarily to the heating cycle of the solar day. The daily migration of this pressure wave around the earth is greatly distorted by local heat transfers but should be identifiable in its fundamental form at an atoll station in mid-ocean. No satisfactory

theoretical treatment of this oscillation has been given and no global description has been attempted to the author's knowledge.

The hypothetical picture of the global diurnal pressure wave given, for example, by Humphreys (1940, p 243) and Godske et al (1957, p 589) calls for a single progressive wave moving with the speed of the sun from east to west with maximum pressure observed at the coldest hours and minimum pressure in late afternoon. Observations on the U. S. mainland seem to support this hypothesis. However, recent work on Atlantic ship and island data (Haurwitz, 1955; Rosenthal and Baum, 1956; Harris et al, 1962) give hours of maximum pressure for the diurnal component ranging from about 1000 LST in the eastern to 2300 LST in the western Atlantic.

Chapman (1951, p 522) on the other hand states that the diurnal component is not a world wide oscillation, yet paradoxically indicates that where unaffected by local peculiarities this component would have a maximum at local noon.

The phase hour of the diurnal tide at Eniwetok is about 0500 and thus seems to agree with the deductions from the continental data. The amplitude of 0.4 mb is, however, about twice the value suggested by Godske et al (1957) as appropriate to "mid-Pacific pinpoint islands".

A hasty review of the literature on this subject leads one to suspect that the observations of the diurnal pressure wave may not be compatible with the hypothesis of a single progressive wave. There may well be a standing wave component which varies with universal time. There would seem to be a strong need for clarification of the nature of this fundamental atmospheric oscillation.

The seasonal variation of the diurnal component of the solar tide appears (from Table 3) to be quite regular. Largest amplitude occurs in late winter associated with latest phase hour. Minimum amplitude and earliest phase hour are found in late summer. This regularity in seasonal trend is unexpected in view of other published results (e.g. Rosenthal and Baum, 1956). Furthermore there seems to be a general consensus of opinion in the literature that the greatest amplitude should be found during the warmest months.

There is greater uniformity of results and hypotheses concerning the semi-diurnal component of the solar tide. Haurwitz (1956) gives the most recent global representation of this oscillation. The annual mean value of this component in Table 2 differs by less than .001 mbs in amplitude and 30 minutes in phase hour from values computed from his functional representation for this latitude and longitude. Haurwitz and Sepulveda (1957) have studied the seasonal variation of this component. The seasonal trend deduced by these authors is strongly supported by the results of Table 3. They hypothesize maximum amplitude in March and minimum in July, as observed. They further expect the earliest maximum to occur in winter and latest phase hour to be found in summer, again in perfect agreement with findings at Èniwetok.

The 8-hourly component of the atmospheric tide has received considerable attention, and a planetary representation of this oscillation has been given by Siebert (1957). The Eniwetok data show no significant disagreement with these results. One of the interesting facets of this oscillation is its near reversal of phase from summer to winter. This is a generally accepted feature of this harmonic and is demonstrated in Table 3.

Surface Wind

The diurnal variation of the wind speed over most land areas is large, consistent, and easily rationalized. Winds tend to be strongest during hours of maximum solar warming and weakest during the cool early morning hours. The mechanism can be ascribed to the diurnal change of stability of the lowest air strata which affects the downward transfer of momentum from the stronger wind flows aloft. Diurnal speed variations over the sea appear to be the subject of some difference of opinion in the literature. Most textbooks of meteorology and climatology supplement the explanation of the continental situation with the statement that since diurnal stability changes are smaller over the oceans the amplitude of the speed variation is reduced. One is still led to expect some speed increase during the day. Bartrum (1957) for example, found a pronounced diurnal speed maximum at noon at Bermuda. The mean diurnal range was approximately 2 mph. On the other hand Brunt (1952) quotes Galle as reporting that at least during months May to October the maximum velocity of the SE trades of the Indian Ocean occurs during the night hours. Riehl et al (1951) in a study of the NE trades between California and Hawaii found an increase in wind speed from noon to midnight. In this latter study only two observation hours were compared, 0100 and 1300 LMT. The speeds were higher throughout the subcloud and cloud layers at 0100 hrs with differences at the surface of about 1.5 mph, reaching a maximum of nearly 4 mph near cloud base. No explanation for these observations was advanced. Riehl (1954) quotes work by Meinardus as well as that just mentioned to confirm the existence of diurnal wind variations at sea. Texts in oceanography, on the other hand, frequently give the impression

that the wind does not vary diurnally on the open ocean.

The mean hourly wind speed without regard to direction at Eniwetok is depicted in Fig 3 for a period of record of 2957 days. The striking similarity of this curve to that for the diurnal pressure variation (Fig 2) is immediately apparent. There can be no doubt that the atmospheric tides are the controlling factor for diurnal variations of surface wind on this atoll. The primary component here, as in the barometric oscillation, is the semi-diurnal.

The theory for the response of the wind to the semi-diurnal pressure wave has been given as early as 1910 by Hann and most recently examined in detail by Stolov (1955). According to this development the winds are antibaric, i.e. they blow anticyclonically around the two low pressure centers and cyclonically around the two high centers. The four pressure cells are strung, equally-spaced, around the equator. Thus at Eniwetok the tidal wind should be from the east as the high pressure cell passes at 1000 hrs, from the south at 1300 hrs, from the west at 1600 hrs as the pressure minimum arrives, from the north at 1900 hrs, etc. Since the prevailing wind is ENE with high steadiness, the tidal winds will account for the maximum speed near 1000 hrs (and 2200 hrs) and minimum near 1600 hrs (and 0400 hrs).

Godske et al (1957, p 590) argue that the winds produced by the diurnal pressure wave should also be antibaric, at least between 30°N and 30°S. This would explain, then, the close similarity between the pressure and wind curves; each component contributes in the same sense to the tidal winds.

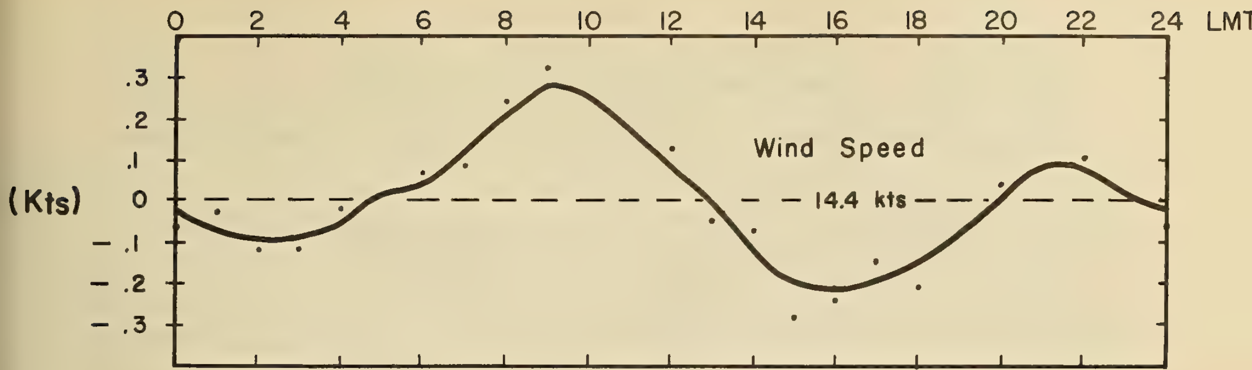


Fig 3. Mean diurnal variation of speed of the surface wind at Eniwetok. Curve shows 3-term running mean; dots are actual hourly values. Dashed line shows mean annual value.

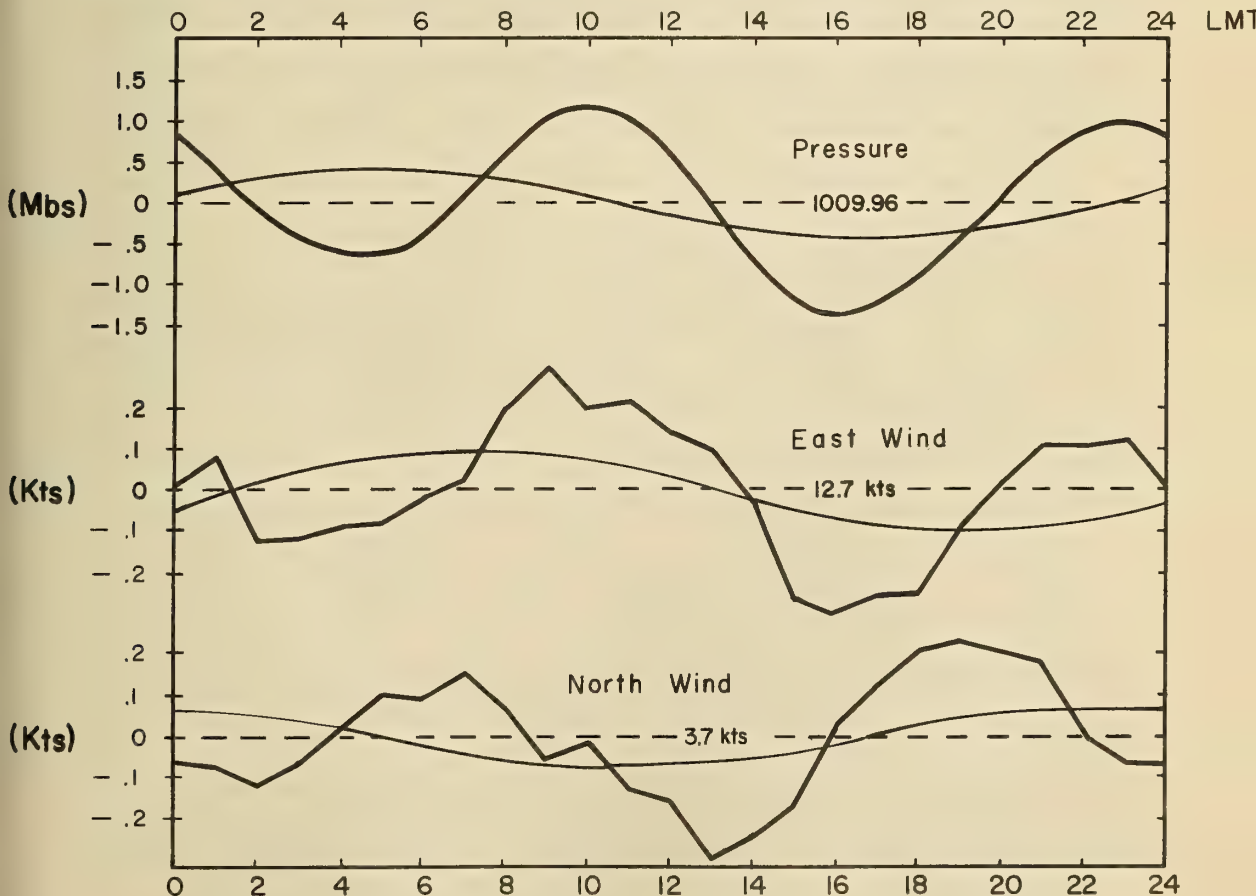


Fig 4. Mean diurnal variation of surface pressure and of East and North components of the surface wind at Eniwetok. Heavy solid lines connect actual hourly values. Thin solid curves are 1st harmonics of the diurnal variation.

In order to examine more critically the relationship between pressure and winds in the atmospheric tides problem, a harmonic analysis was made of the hourly mean wind vector. The data were not ideal for this purpose since wind direction was reported to only 16 points of the compass. This decreases the sensitivity of the data somewhat but the period of record is probably long enough (2715 days) to surmount this difficulty.

The diurnal curves of observed east (u) and north (v) components along with sea level pressure (P) are given in Fig 4 together with the 24-hour harmonics computed therefrom. It is of interest to compare both the 24- and 12-hour harmonics (from Table 2) with those expected from theory for the latitude and longitude of [illegible]. This is done in Table 4.

TABLE 4

Comparison of Observed and Predicted Air Tides.

	Diurnal Component		Semi-diurnal Component	
	Observed	Godske *et al*	Observed	Stolov
u (cm/sec)	± 5.0	unknown	± 10.3	± 22.8
v (cm/sec)	± 3.5	unknown	± 9.3	± 10.6
t_u (hrs)	7.11	4.53	9.99	9.81
t_v (hrs)	22.29	22.53	6.76	6.81
P (mbs)	± 0.39	± 0.2	± 1.03	± 0.93
t_p (hrs)	4.53	≈ 5 a.m.	10.04	9.81

Considering first the semi-diurnal component it is seen that the agreement is very good with regard to phase but that the predicted amplitude of the tidal motion is too high. This may perhaps partly be due to frictional retardation which was not included in Stolov's development or to a faulty representation of the amplitude of the pressure wave at these

latitudes. Stolov utilized Simpson's formulation composed in 1918. The predicted value of 0.93 mbs pressure amplitude is based on this expression.

The diurnal component, as mentioned earlier is much more poorly understood. There is, however, sufficient agreement with the ideas expressed by Godske et al (1957) to lend strong support to the idea that this variation is due primarily, if not completely, to a global tidal phenomenon. If there exists any residual diurnal wind variation not due to air tides, it must indeed be small. Close examination of the first two columns of Table 4 will reveal, however, some argument for the reality of such a small diurnal effect. It will be noted that the phase hour of the v component follows expectation very closely while that for the u component is advanced by more than two hours. For the sake of argument we may suppose that the wind speed at the surface increases slightly toward mid-day as it does over land. Since winds are predominantly easterly this effect would be felt in the u component but hardly at all in the v. The effect would be essentially to superimpose a second daily cosine curve which would tend to pull the early morning maximum of u toward noon and increase it amplitude somewhat. This shift relative to the pressure wave is observed (see Fig 4). Certainly, the data do not warrant definitive conclusions from such minute effects. It does seem plausible though that the "local wind" variation, apart from air tides, is limited to a speed increase with a maximum near noon of amplitude about 3 cm sec^{-1} or about .07 kts. There is, of course, no way of knowing whether this, if realistic, is representative of the atoll only or of the open ocean. After consideration of stability variations in the lower air over the open ocean it becomes more reasonable to ascribe this effect to the atoll.

Before leaving the subject of atmospheric tides it might be of interest to consider briefly the seasonal trend of the wind variation to see how closely it agrees with that of pressure.

Fig 5 depicts the seasonal trend of both the amplitude and phase hour of the 1^{st} harmonic of pressure and wind components. A very curious feature presents itself here. The phase hour of pressure varies slightly but regularly as noted earlier. The phase hours of the u and v components, however, show a peculiar tendency to move steadily around the clock (in opposite directions) with the seasons. The feature may quite likely be spurious. If it is real, the explanation for it escapes the writer. The amplitude variation does demonstrate that a certain degree of randomness is present.

Fig 6 gives a presentation similar to that of Fig 5 for the semi-diurnal harmonic. Much greater correspondence is demonstrated here between the three variables, and the theory of atmospheric tides is quite well verified.

Low cloudiness

The great difficulty of securing accurate observations of middle and high clouds is well known. The situation is not helped at all by the prevalence of opinion (particularly in the 1940's) that the tropical sky is usually covered by a veil of cirrostratus -- whether or not it can actually be seen. Furthermore, observing high cloud at night is notoriously difficult. For these reasons, taken together with the objective of assessing the atoll influence, only low cloud data are examined in this report.

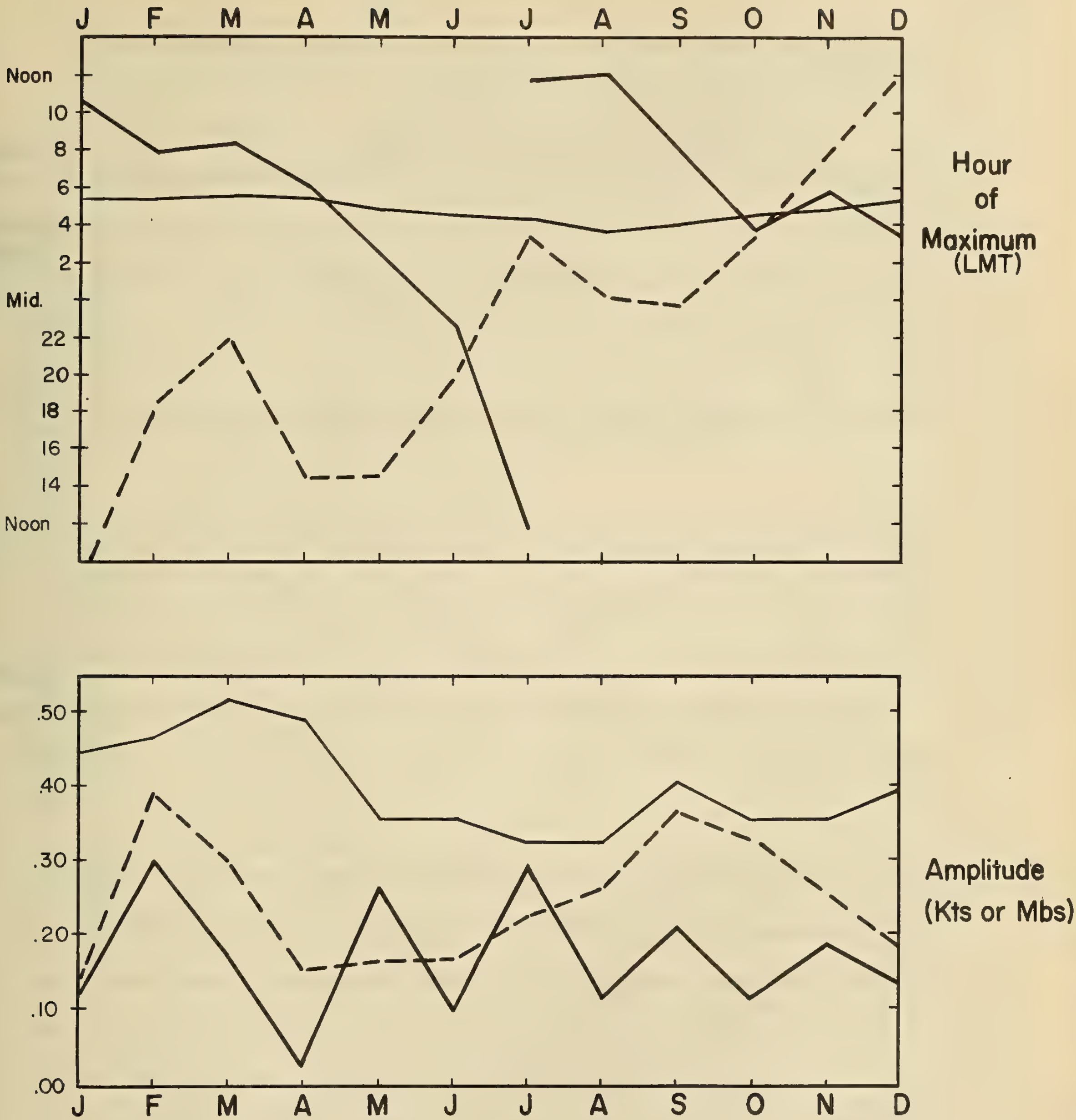
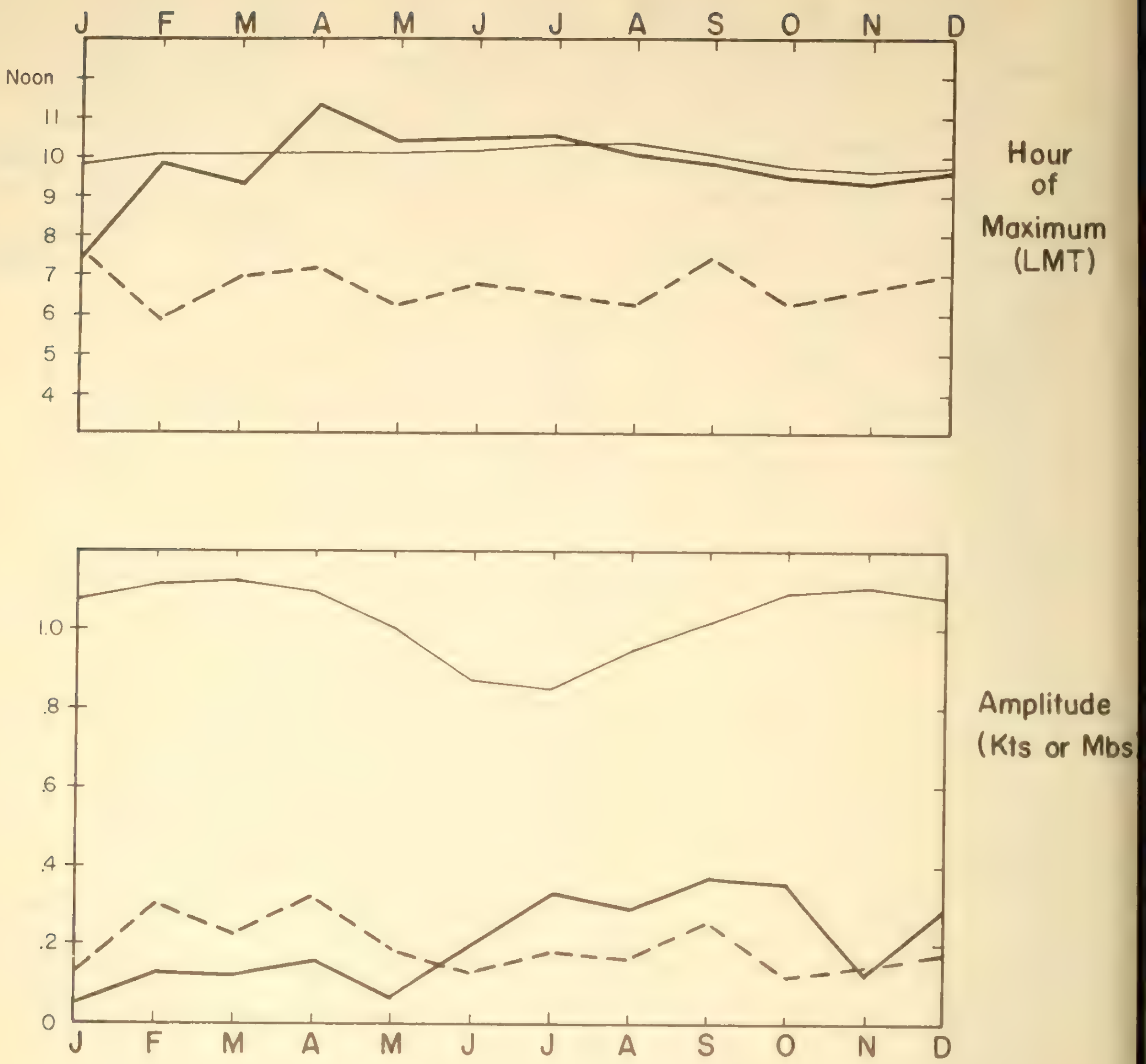


Fig 5. Seasonal trend of amplitude and phase hour of the 1st harmonic of pressure and wind components at Eniwetok. Heavy solid curves depict East wind component, dashed curves refer to North wind component, and thin solid curves refer to pressure.


J F M A M J J A S O N D
Noon
11
10
9
8
7
6
5
4
Hour of Maximum (LMT)
1.0
.8
.6
.4
.2
0
Amplitude (Kts or Mbs)
J F M A M J J A S O N D

The same precautions taken with the processing of other variables were followed with the cloud analysis, resulting in the selection of 2719 days of homogeneous data. No distinction was made between cloud types or cloud heights provided they were classified as stratus, strato-cumulus, cumulus, or cumulonimbus. The overwhelming majority of low cloud types reported, however, was cumulus with bases at about 1800 ft. Whenever low clouds were reported at several levels the amount reported under a column titled "summary amount" was recorded. This latter value gives the decimal cover by all low cloud.

An analysis of the seasonal trend of the diurnal variation of cloudiness is given in Fig 7. The isopleths are based upon hourly values of low cloud amount expressed as percent deviation from the individual monthly mean. Monthly mean values vary little throughout the year, having a maximum of 3.2 tenths low cloud cover in May and minimum of 2.8 in September.

Fig 7 demonstrates some consistency in the diurnal variation throughout the year. Each month shows an increase in low cloud from midnight or earlier through the early morning hours. This feature is undoubtedly real. The only distinct seasonal trend is the tendency for an afternoon maximum in cloudiness to develop during the summer months, July through November. These months encompass the season of weakest trades, maximum sea surface temperatures, and greatest instability in the lower atmosphere. It is possible that the afternoon maximum during this season is brought about by the increased frequency of calms or light winds which result in greater heating of the surface waters during early afternoon. The atoll heat source would be expected to have its maximum effect under the same

Fig 7. Diurnal variation of low cloud amount by months at Eniwetok expressed as precent deviation from the monthly mean. Grid pattern shows maxima, hatched areas are minima.

circumstances so that the two are difficult to separate. The results of the analysis reported in Part I are probably not sufficiently sensitive to uncover such slight variations of cloud amount. However, resumes of oceanographic cruises occasionally indicate a secondary maximum after noon (e.g. Garstang, 1958).

The main features of Fig 7 are quite evident in Fig 9 which depicts the annual mean diurnal variation curve. The daily range of cloudiness is seen to be quite small, 10-12% of the mean or 3.7% of total sky. The primary characteristic of the curve is undoubtedly the pronounced maximum at about 0700 and minimum near 2200 hrs. The small secondary maximum just after noon is the contribution of the weak trade season discussed in the previous paragraph.

There appears to be general agreement in the literature concerning the tendency toward maximum low cloudiness over oceans during the early morning hours although detailed studies of this point are very few. Riehl (1947) investigated data for 920 observing days from three ship stations near 35°N in the Atlantic Ocean. Using 3-hourly observations only, he found the diurnal variation of low cloud to be similar at each ship with a maximum at 0600 hrs (3.4 tenths) and minimum at 2100 hrs (3.2 tenths). These results show remarkable agreement with those reported here.

These results may be said to support the conclusions from Part I concerning the absence of a significant influence of the atoll upon low cloudiness. If the diurnal variation of cloud over the atoll differs negligibly from the variation observed at a ship station, one is led to believe that the influences of the two observing platforms differ

negligibly. Again, caution must be taken to admit the possibility of a systematic influence which does not react to the daily heating cycle. It seems clear, however, that textbook statements on the subject such as (Riehl, 1954, p 111): "Even atolls have a definite effect on the local cloud structure and its diurnal course", do not apply at Eniwetok.

If there can be said to be some consensus of opinion concerning the character of the diurnal variation of low cloud over the sea, there is yet little evidence of agreement on its cause. A discussion of hypotheses will be postponed until the nature of the hourly trend of precipitation is explored. It seems reasonable to consider the explanation of these two features in tandem.

Precipitation

The reality of the oft-reported nocturnal rainfall maximum over the ocean has never been fully investigated. The objection raised against most published records which demonstrate the existence of such a feature is that possible coastal or island influences have not been excluded. Certainly, most of the long term data on oceanic precipitation has been gathered on continental coastlines or on rather large mountainous islands. In either case it is difficult to evaluate the effects of land-sea breeze regimes, orography, and mountain-valley winds upon the "undisturbed" precipitation pattern. Nevertheless, it is common practice among climatologists to distinguish between maritime and continental precipitation regimes according to whether the diurnal maximum occurs by night or by day. The question remains, however: is the "maritime regime" representative of open ocean or only of coasts? Shipboard observations of precipitation are generally confined to occurrence versus non-occurrence.

Fig 8. Same as Fig 7 but referring to precipitation occurrence.

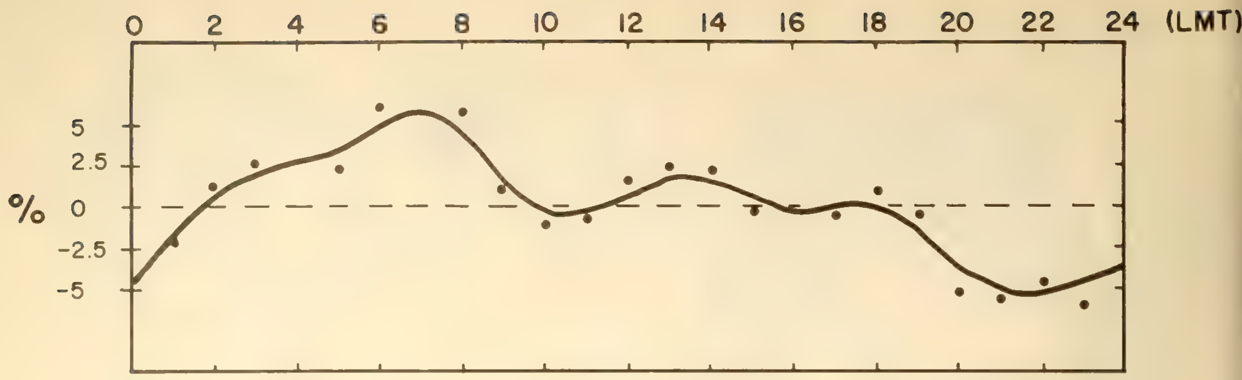


Fig 9. Annual mean diurnal variation of low cloud amount at Eniwetok. Deviations are in percent of annual mean (2.93 tenths). Solid curve is 3-term running mean of hourly values (heavy dots).

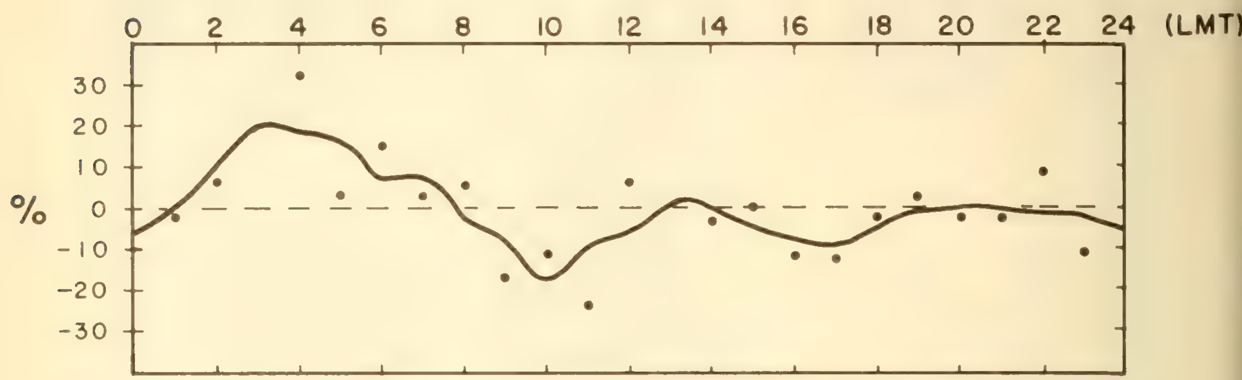


Fig 10. Same as Fig 9 but referring to precipitation occurrence at Eniwetok.

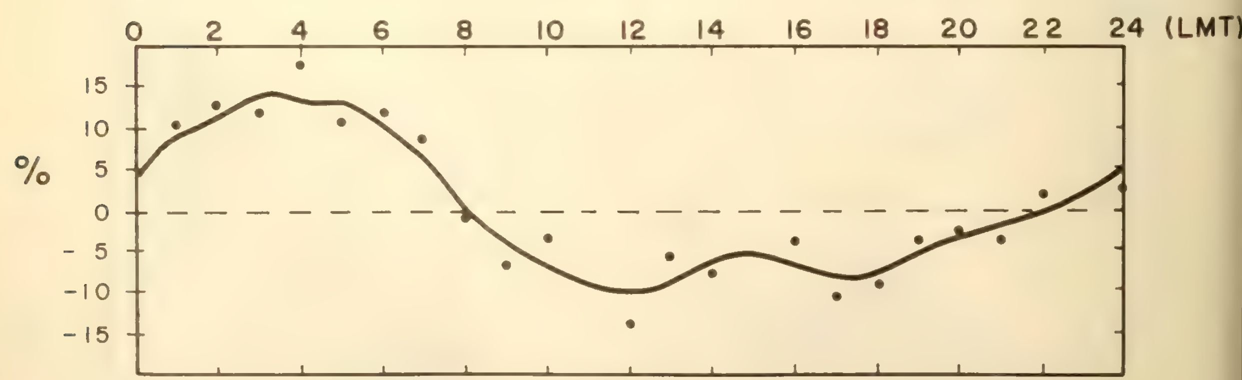


Fig 11. Same as Fig 10 but composited from precipitation occurrence at Wake, Kwajalein, Majuro, Johnston, Marcus, Canton, Christmas, Fanning and Palmyra Islands.

Furthermore these are generally limited to the 6- or 3-hourly synoptic reports. Still, a wealth of data exists in this area which has never been tabulated to this author's knowledge.

The hourly airways observations available for Eniwetok are meant to be a valid characterization of the weather between 2 and 5 minutes before the hour. Thus a shower which ends just before observation time is not recorded in the weather symbols. This effects a drastic reduction in the actual frequency of rain occurrence and reduces the size of the data sample considerably from the point of view of determining hourly variations. Rain amounts were totaled over 6-hourly periods, hence these are of only limited use in the characterization of diurnal variation.

Fig 8 gives a representation of the seasonal trend in the diurnal variation of precipitation occurrence at Eniwetok. Nearly 9 years of hourly totals were expressed as percent deviations from the monthly mean for the purpose of this analysis. From the foregoing discussion of the data it is to be expected that considerable randomness was evident in the actual values. These were first smoothed by a 3 term running mean process before analysis.

Some meaningful pattern is evident in Fig 8. There is an unmistakable nocturnal maximum in all months although it exists as only a secondary maximum in October (the wettest month). Definite seasonal trends are difficult to establish, however. In view of their tentative nature, seasonal differences will not be elaborated further. There would, indeed, appear to be justification for combining all months to reduce meaningless fluctuations.

Fig 10 summarizes the annual mean variation. The diurnal range of

hourly rain occurrence is seen to have a range of about 40% of the mean with a maximum between 0300 and 0400 hrs and a minimum near 1000 hrs. The secondary maximum between 1300 and 1400 hrs is largely a fortuitous feature as can be shown from Fig 8. In fact a broad minimum centered in the early afternoon appears to be a reasonable interpretation of Fig 8.

There seems to be little doubt that a significant early morning maximum in precipitation exists at Eniwetok. However, in view of the random fluctuations in the diurnal curve (Fig 10), certification of this point by examination of records from other atolls was felt to be desirable. A copy of Navy Job #3606 (1960) was secured from the National Weather Records Center for this purpose. This data summary presents an hourly tabulation of rainfall occurrences by month for several Pacific stations. This summary included the following atolls: Wake, Midway, Kwajalein, Majuro, Johnston, Marcus, Canton, Christmas, Fanning, and Palmyra. The periods of record varied from about 1 to 13 years, and the frequency of hourly observations was far from uniform. Still when the individual station records were normalized, all but one, Majuro, showed a definite nocturnal maximum falling between 0200 and 0400 hrs. A composite diurnal curve of all of these atolls is given in Fig 11 where the time scale refers to zone time for the nearest standard meridian. The composite was constructed by simply adding corresponding hourly total rain frequencies (after normalizing each to a representative observing frequency) and then computing deviations from the grand mean. Thus each station was essentially weighted according to its length of record. The curve represents the hourly distribution of a total of 35,700 individual observations of rain on the ten atolls.

The diurnal variation appears, from Fig 11, to be rather small. However, it must be kept in mind that most of the rainfall on these tiny islands is the consequence of the passage of synoptic disturbances. Certainly the convergence patterns associated with these must frequently overpower any tendency for diurnal regulation by the oceanic regime. Thus the diurnal range of about 25% (of the mean) would seem to be indicative of a real effect which demands explanation.

Nevertheless, it is troubling to find exceptions to this general diurnal trend and this may have deterred researchers from attempting a definitive explanation of the phenomenon. Ramage (1952), for example, found an insignificant and confused diurnal pattern on several island stations up to a few hundred miles off the Asiatic continent. At the same time most coastal stations showed a distinct early morning maximum. Of the atolls composited in Fig 11 Majuro is strikingly dissimilar in its diurnal march of rain occurrence. This atoll resembles Eniwetok in its physical features and in the location of its observing station relative to the lagoon and prevailing winds. It differs from Eniwetok, however, in its proximity to another atoll, Arno, some 10 miles to the east. Majuro is also situated in the Marshall Islands some 600 nautical miles ESE of Eniwetok at about 7°N, 171.5°E. Fig 12 gives the diurnal curve of precipitation occurrence at Majuro tabulated from the station's Local Climatological Data (April 1958-August 1961) published by the U. S. Weather Bureau. These data are superior to those tabulated from Airways reports since they reveal the number of hours during which rain was observed at any time during the hour. The lower curve in Fig 12 shows a peculiar trend with the typical sharp increase in rain frequency from midnight to 0300 hrs followed by steady values throughout the

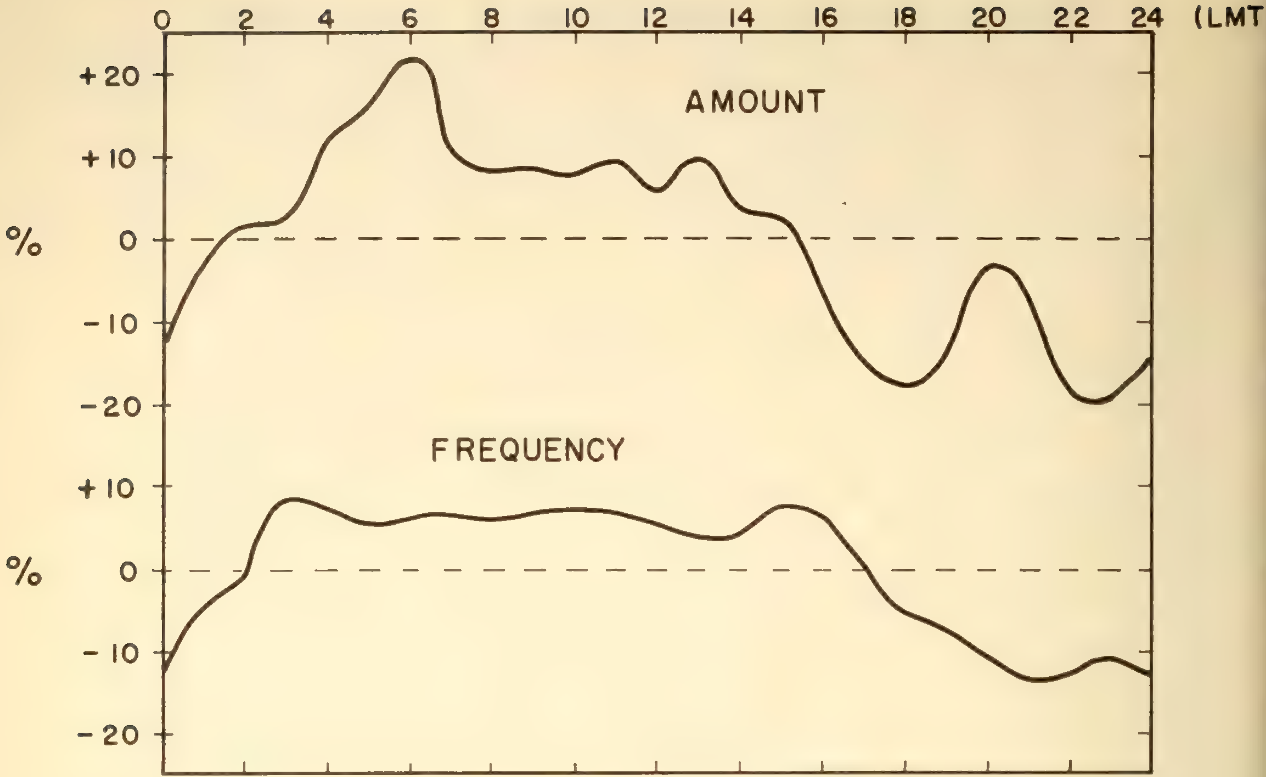


Fig 12. Annual mean diurnal variation of precipitation amount and occurrence at Majuro Atoll. Curves are 3-term running means of hourly values and describe percent deviation from annual mean.

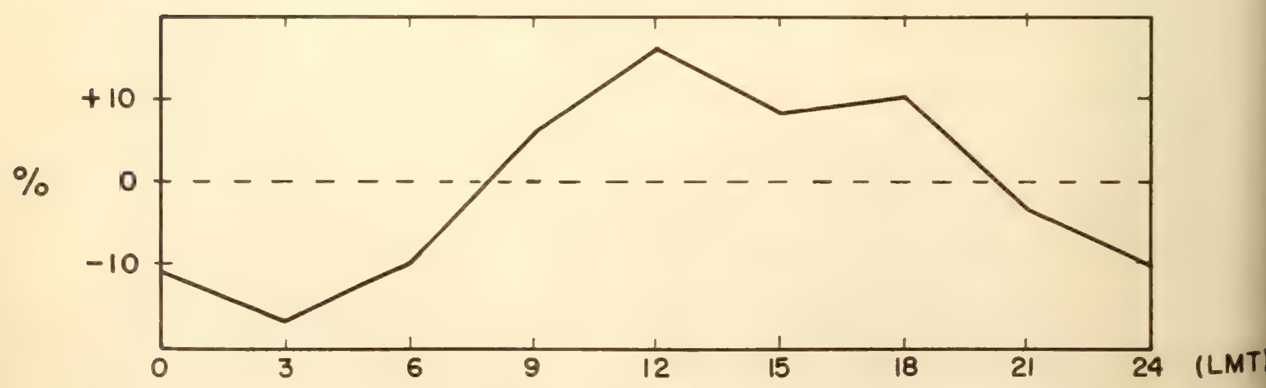


Fig 13. Annual mean diurnal variation of precipitation occurrence at Ship N (30°N, 140°W) taken from 3-hourly observations.

morning and until mid-afternoon. The upper curve shows the trend of hourly amounts taken by recording rainguage and extracted from the same source and time period as the first curve. An early morning maximum is evident here indicating that showers, if not most numerous, are at least most intense at about 0500-0600 hrs. It appears, then, that the "maritime influence" predominates here, but it may be contaminated by a downwind effect from Arno Atoll which has substantial land area.

A final piece of contradictory information will be included for the sake of completeness. Fig 13 depicts the diurnal rain occurrence trend at Ocean Station Vessel November positioned between Hawaii and California at 30°N, 140°W. The period of record is January 1952 to June 1958. Data are from 3-hourly observations tabulated from Job #3606 (1960). Fig 13 indicates a diurnal trend which is about 180° out of phase with that quoted for atoll stations. No explanation for this phase reversal will be attempted here, but it may be compatible with observations of minimum height of the trade wind inversion during the night in this region. An explanation for such a diurnal variation of the strong inversion in the northeast trades at this location has been offered by Neiberger (1958). It was hypothesized that a standing wave is produced in the inversion layer by the forcing action of the sea breeze divergence at the coast. The height of the inversion base has a fundamental control on the development of precipitation at this station; a forced oscillation of this layer could undoubtedly exert primary control over shower frequency.

In summarizing the observations of diurnal variation of precipitation over the open ocean it is safe to say that the great preponderance of data indicates the reality of a late nocturnal maximum. It must be admitted

that exceptions can be found even on tiny islands or ship stations. However, it is likely that these can be successfully treated as exceptions, and other over-riding considerations may be found. From what has been deduced about the effect of atolls upon diurnal variations, it must be concluded that the phenomenon is at least representative of the mid-Pacific oceanic regions within the tropics. In view of this, it would be desirable to consider possible hypotheses in the light of the picture being constructed here from Eniwetok data.

The fundamental cause of a diurnal variation must be the sun, but the immediate causal agent could take several forms. Atmospheric tidal fluctuations appear quite incapable of bringing to bear an intensity of convergence greater than about 5×10^{-5} sec^{-1}. At low cloud levels this could not induce vertical motions greater than 10^{-2} cm sec^{-1}. These must be considered negligible. Furthermore it has been noted earlier that the oscillation in the wind field is primarily semi-diurnal in character.

If the nocturnal maximum cannot be ascribed to a diurnal variation in convergence, we must look to the convectional-precipitation mechanism itself for a clue. Let us examine, for the sake of completeness, the variables which might possibly influence the precipitation potential of a cumulus cloud in the tropics. We have:

1. spectrum of condensation nuclei
2. cloud base temperature
3. updraft speed
4. turbulence spectrum
5. cloud depth
6. vertical shear of the wind

7. humidity of the cloud free air
8. width of cloud thermals
9. lifetime of the cloud
10. electrical properties of the cloud.

Information is lacking for a detailed consideration of each of these factors. However, we have no reason to suspect a diurnal variation in factors 1, 6, and 8. Factor 2 appears to be insignificant since there is no detectable diurnal variation in the reported heights of cumulus cloud bases, and free air temperature variations are small. Factors 3 and 4 depend largely on vertical stability in the convective layer. The diurnal trend of this variable should certainly be considered. Factor 5 will also be affected by the foregoing, particularly with regard to the height of the inversion or stable layer which limits development. Factor 7 undoubtedly has a diurnal variation though it is more likely to be an effect in this case than a cause. Factor 9 quite likely varies diurnally, but here also this could result from individual clouds being better developed at night and therefore requiring longer to decay. It is not a fundamental consideration here. Factor 10 is difficult to assess. However, it is well known that most atmospheric electricity parameters undergo a diurnal variation which, over the oceans, follows universal, not local time.

From cursory examination of the problem, then, it seems that a variation in vertical stability below or within the cloud layer and/or a variation in height of the inversion (or stable layer) must be suspected. We have ruled out as highly unlikely the possibility that the micro-physics of night-time clouds differs significantly from their daytime counterparts. Since individual clouds are short-lived, the colloidal stability of new

cloud matter would have to change in some pregressive fashion through the night to account for the rainfall trend. Likewise day or night will have a negligible effect upon the evaporation of raindrops between cloud and ground.

In order to examine the effect of thermal stratification on maritime cumulus we must first recognize an important distinguishing feature of these clouds, i.e. the absence of low-level convective"roots". Most observational evidence points toward an origin very near cloud base for most maritime cumulus updrafts. Thus the instability from which these clouds are born does not manifest itself in the surface layers as much as within the cloud layer itself. In this view, the heat supplied by the ocean surface (in the trades at least) is mixed upward by small scale eddies rather than organized thermals. This of course will not be the case if the sea is "sufficiently" warmer than the air. The exact stimulus for formation of such a cloud is an unsettled question but probably arises from either organized or random internal waves or turbulence at these levels which is able to cause sufficient vertical displacements to result in condensation. The conditional instability within this layer will allow such a cloud to grow until it reaches a stabilizing layer. One might expect, then, the variation in stability within and at the top of the cloud layer to have a controlling influence on cloud depth and also on rainfall. Let us for the moment concentrate our attention upon this 1 to 2 km layer.

Under trade wind conditions at the longitude of Eniwetok there seldom exists a pronounced inversion. The trade wind cumulus is usually capped instead by a layer of relative stability which is associated with an

increased lapse of mixing ratio with height. With clear air then, the the calculation of the divergence of flux of terrestrial radiation will show maximum cooling rates near the base of this stable layer. This effect would seemingly cause reduction of stability below (and enhancement of stability within) the stable layer. However, such a radiational influence would be felt as strongly during the day as at night. The small absorptivity of solar radiation by water vapor would tend to reduce the cooling rate slightly but this effect alone would appear to have a small influence upon lapse rates in the layer under consideration.

At any rate, clouds cannot be left out of the picture for they are typical of the trade wind regime (mean and modal low cloud cover is about 3 tenths at Eniwetok). Again, quantitative values are elusive, but the direction of influence of clouds upon the radiational heat exchange of their environment is well known. A cloud whose depth approaches 50 m or more can be considered a black body for terrestrial radiation. The cloud top thus radiates much more energy than it receives from the dry air above the stable layer and this upper 50 m or so of cloud cools steadily. In fact the deeper its penetration into the stable layer the less downward radiation it receives since moisture typically drops off rapidly with height.

Each individual cloud has a lifetime approaching a half hour. The upper radiational cooling is thus not likely to cause much change in the development of that particular cloud. But, the effect may be cumulative since the entire cloud layer is destabilized progressively by the effect of each cloud within it. This might allow each successive cloud to develop to a slightly greater depth. Under favorable conditions a few

hundred feet of cloud depth gained in this way might well spell the difference between success or failure of the coalescence mechanism to run its course.

It remains of course to demonstrate that this chain of events is suppressed in daytime. Sufficient absorption of solar energy by the cloud tops would contribute to this both by tending to evaporate cloud droplets, thereby retarding coalescence growth, and by reducing the instability of the cloud layer. Quantitative measures of absorptivity of clouds for solar radiation may be insufficient to allow a definitive computation of this effect.

It must be kept in mind that the high reflectivities of cumulus clouds are the result of volume scattering. This results in a very large intensity of radiant energy in the upper portions of clouds and a rapid decrease of this intensity with depth. Thus with a constant absorptivity (fraction of energy absorbed to that incident upon a slab) most of the absorption is accomplished by the upper layers of the cloud.

From the measurement of total absorption of cloud layers of various depths (Fritz and MacDonald, 1951) it would be reasonable to expect a cumulus cloud of 2 km depth to absorb at least 10% of the energy incident upon its top. Let us assume that 3% is absorbed by the upper 100 m of cloud. This is not inconsistent with the theoretical results of Hewson (1943). Assuming all of this energy is used to raise the temperature of the cloud mass, the rate of change of the temperature, T, with time is given by:

$$Mc_p \frac{dT}{dt} = \frac{dQ}{dt} = .03\ I_o \qquad \ldots\ldots\ldots\ldots\ldots\ldots \qquad (2)$$

where M = mass of upper 100 m of cloud

c_p = specific heat at constant pressure of cloudy air

I_o = rate of incident radiation per cm^2

Q = heat added

Since the clouds will be continuously forming and dissipating, the effect of this absorbed energy will be to provide heat to the layer of clear as well as cloudy air at that elevation. Since typically about 20% of the layer may include cloud at one time the heat must be distributed over 5 times the area over which it is received. We have then

$$M = 5 \times 10^4 cm^3 \times 10^{-3} gr\ cm^{-3}$$

$$c_p = .24\ cal\ gr^{-1}\ {}^oK^{-1}$$

and

$$\frac{dT}{dt} = \frac{.03 \times 1.7}{50 \times .24}\ {}^oK\ min^{-1} = .26\ {}^oK\ hr^{-1}$$

Even if allowance is made for eddy diffusion of this heat upward and downward, a heat source of this magnitude must be considered significant. This is true since the lower portions of the cloud layer are benefitting very little from such heating. This differential heating can easily change the lapse rate within the layer by over $\frac{1}{2}{}^oC\ Km^{-1}$ in 6 hours. Under the delicate balance which exists in the oceanic convection layer the result upon individual cloud buildups could be substantial. The effect would be cumulative, reaching a maximum after noon, and would allow long-wave radiation to provide cumulative destabilization of this layer throughout the night.

It must be stressed that there is no reason _a priori_ to expect that the variation of low cloud amount would parallel that of shower frequency,

although some interaction could be expected. Without increasing the number or size of clouds substantially, a large increase in rainfall probability could be achieved. The cloud depth is the most critical factor. Eventually, increased shower activity might well result in more scud-type cloud fragments and more persistent stratiform "aprons". The cloud variation might then be expected to lag the shower variation if the latter were the primary effect. Riehl (1947) in seeking an explanation for the early morning maximum in low cloud at Atlantic ship stations, attempted to test a radiation hypothesis. He sought differences in the nocturnal cloud increase between nights with considerable middle or high cloud and nights with little or none. His results could not lend support to any radiation mechanism. No attempt was made to repeat the experiment with Eniwetok data. In the development given here, however, it is not necessary to involve the variation of low cloud amount in the mechanism for rain production.

In meteorology it generally seems to be a mistake to look myopically upon a single factor to explain a complex phenomenon. Other influences can be found which may contribute in the same sense as the mechanism described here. The most important of these is probably the diurnal variation of sensible heat transfer across the air-ocean interface. Even with the "rootless" convective regime described earlier as being representative of this region, any change in the rate of heat transfer at the lower boundary must carry some influence to the cloud layer. However, it is more likely that a slight increase in ocean surface heating would result primarily in more cloudiness and have only a secondary effect on showers.

Diurnal changes in sensible heat transfer at the ocean surface are

admittedly small, but under tropical conditions these may be important. The main determinant of this transfer is, of course, the air-sea temperature difference. Extended periods of accurate monotoring of this variable have been rare, in the tropics particularly. Interesting results from a 16 day, "on station" cruise by the Woods Hole vessel, CRAWFORD, at about 11°N, 52.5°W have been reported by Garstang (1958). Detailed measurements of air and sea temperatures revealed that on the average, maximum upward sensible heat transfer took place between 0500 and 0600 hrs. From 0900 to 1700 hrs the transfer was actually negative, that is from air to sea. This state of affairs resulted primarily from the observation that the air diurnal temperature variation as measured aboard ship was large (2.7°F) compared to that of the sea surface (1.1°F). Thus even though the sea is slightly warmer than the overlying air in the mean, the air becomes warmer than the sea toward mid-day. A similar effect may be found in the data collected by the METEOR Expedition (Kuhlbrodt and Reger, 1936). Radiation errors in air temperature measurements during daylight could contribute to this result. However, Jacobs and Clarke (1943) observed the same effect aboard the CARNEGIE even after correcting for radiation error, although the sea-air temperature difference usually remained slightly positive with a minimum before noon. The explanation for the greater diurnal range in the air temperature probably rests upon the active participation of surface air in the radiational transfers. It cools by night more rapidly than the sea surface (with its large heat reservoir) and likewise absorbs sufficient solar radiation by day to increase its temperature at a rate significantly greater than that of the sea.

In summarizing these conjectures dealing with the diurnal variations

of cloudiness and precipitation over the sea, it seems that the <u>absence</u> of a nocturnal maximum would be surprising. Only under light wind conditions could convincing arguments be made for an afternoon maximum of cloudiness and possibly of precipitation also. It has been suggested here that the primary mechanism leading to an early morning maximum in shower activity is the cumulative effect of nocturnal cooling of ever-present cloud tops. This leads to a steady destabilization of the <u>cloud layer</u> which causes individual clouds to have maximum development toward daybreak. The effect may be self-limiting because of increased covective mixing. Therefore the maximum activity may occur well before sunrise. Also, during the night upward transfer of sensible heat is increasing from the lower boundary with the result that clouds are more easily formed and somewhat more numerous near sunrise. This latter effect probably has little direct influence on the precipitation potential of each cloud, however. Shortly after sunrise both of these trends are reversed. The upward flux of sensible heat decreases rapidly, reducing slightly the occurrence of cumulus cloud elements (after some lag). The solar radiant energy absorbed by the cloud tops is slowly spread through much of the upper portion of the cloud layer, and the layer becomes steadily more stable. The reduction in cloud depth in turn limits the precipitation mechanism.

<u>Temperature and humidity</u>

Radiational heating and cooling of thermometers have some influence upon diurnal temperature variations measured within a standard instrument shelter. This is also true to a lesser extent for relative humidity and wet-bulb temperature. The extent of the error so introduced will, of course, depend upon the quality of the shelter, its exposure and the technique used

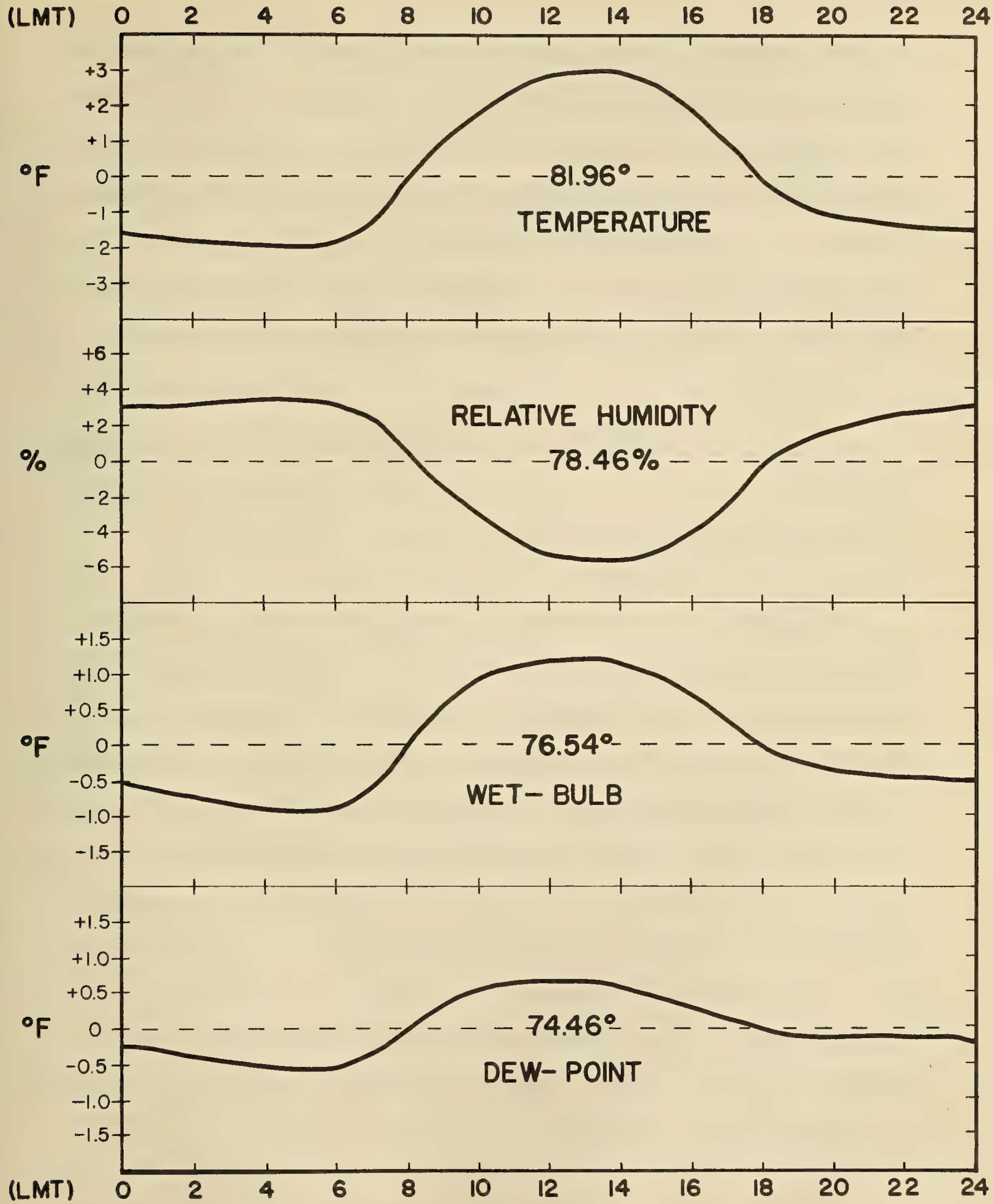


Fig 14. Annual mean diurnal variation of surface temperature, relative humidity, wet-bulb temperature, and dew-point at Eniwetok. Curves connect hourly mean values expressed as percent deviations from annual means (values shown).

in taking readings. None of these factors is known for the Eniwetok data. It is likely that the standard white, wooden, louvered thermometer screen was used and that it was located over coral fill. If a good fan driven ventillation system was used in the shelter or if psychrometer readings were taken in ventillated shade, it is likely that the true daily temperature range is not exaggerated by more than 1 or $1\frac{1}{2}$°F. The only humidity measure which should not be affected by such errors is the dew-point temperature (T_d).

The annual mean diurnal variation of temperature and of three humidity variables is portrayed in Fig 14. The first four harmonic components of each of these curves will be found in Table 2 (page 13).

The diurnal temperature range is seen to be about 5°F. This can perhaps be compared with the range of 2.7°F reported by Garstang (1958) as appropriate to shipboard observations at the same latitutde in the Atlantic. Results of Cruise VII of the CARNEGIE (Jacobs and Clarke, 1943) at these latitudes, largely in the Pacific, show a range of 3.1°F. Radiation errors in these values are probably of the same magnitude as those at Eniwetok. The influence of the atoll, then, upon the air temperature at $4\frac{1}{2}$ ft measured at Eniwetok Islet is probably such as to cause warming of about 1.5°F at mid-day and perhaps less than 0.5°F cooling during early morning. These rough estimates are supported by a short analysis (not included here) made of the raw data presented by Blumenstock and Rex (1960) for a short study at Eniwetok.

The diurnal variation of wet-bulb temperature (T_w) and of relative humidity (R.H.) conform to expectation, at least as far as phase is concerned. Table 2 reveals exact correspondence between the phases of the

diurnal components (t_1) of T and T_w while that of R.H. is just reversed. The semi-diurnal components (t_2) of T_w and T reach maxima within 25 minutes of each other; at the same time the 12-hour component of R.H. reaches its minimum. The foregoing would be the case even if the vapor content of the air did not vary diurnally. T_d, however, should measure this latter variation faithfully (once the pressure change effect is acknowledged to be negligible). The dew-point curve demonstrates that the moisture content of the lower air follows the temperature curve very closely. The diurnal range of about 1.2^{o}F for T_d corresponds to a range of about 1.2 mbs for vapor pressure or approximately 0.8 gr Kg^{-1} for mixing ratio. The range in dew-point computed from mean data on T and R.H. provided by Garstang (1958) from ship measurements is about 0.5^{o}F. The mean diurnal range of vapor pressure in this region of the Pacific shown in the records of the Carnegie Cruise (Jacob and Clarks, 1943) is about 0.7 mbs. We might then conclude that about half of the indicated diurnal range of moisture content at Eniwetok is due to the atoll influence. Presumably the soil and reef waters are sufficiently warmed to cause increased evaporation near mid-day compared to the open ocean.

It may be somewhat surprising to find so little correlation between the curves in Fig 14 and the diurnal rain frequency curve (Fig 10). There is no doubt that temperature and humidity respond very strongly to the presence of a shower; apparently the period of record is sufficiently long and showers are infrequent enough to allow the curves in Fig 14 to be essentially independent of rain occurrence.

Rawinsonde information

The Eniwetok card file utilized in this study included rawinsonde data at standard pressure levels for the 6 year period, January 1954 through December 1959. This card deck was processed for diurnal variations which might elaborate or clarify some of the problems which have been dicussed for surface measurements. For this limited objective, only low levels were examined, and the results presented here are not designed to make a contribution to the interesting problem of diurnal variations in the free atmosphere.

Soundings at Eniwetok are normally made at 12 hour intervals. During three separate periods of nuclear testing, however, soundings were routinely made at 6 hour intervals with frequent special observations. These test periods each lasted from 2 to 6 months. About halfway through the period of record the standard hours of soundings were changed from 0300 and 1500 LMT to 0000 and 1200 LMT. The card file as a whole, then, covers the hours of the day fairly well in spite of its inhomogeneity.

In order to extract some idea of diurnal trends from this record the cards were examined sequentially, and forward differences were taken of the variables of interest. Only 6 or 12 hour intervals were accepted for differencing, however. When the interval between soundings was 12 hours (± 1 hr) the change in the variable was divided by two and this value was assigned to the median hour. Thus, the change in the value of a quantity which is recorded at 0800 hrs could be due to differences between 0200 and 1400 LMT soundings or to the observed change from a pair of soundings taken at 0500 and 1100 LMT. In either case the recorded difference would be appropriate to a change *per 6 hours*.

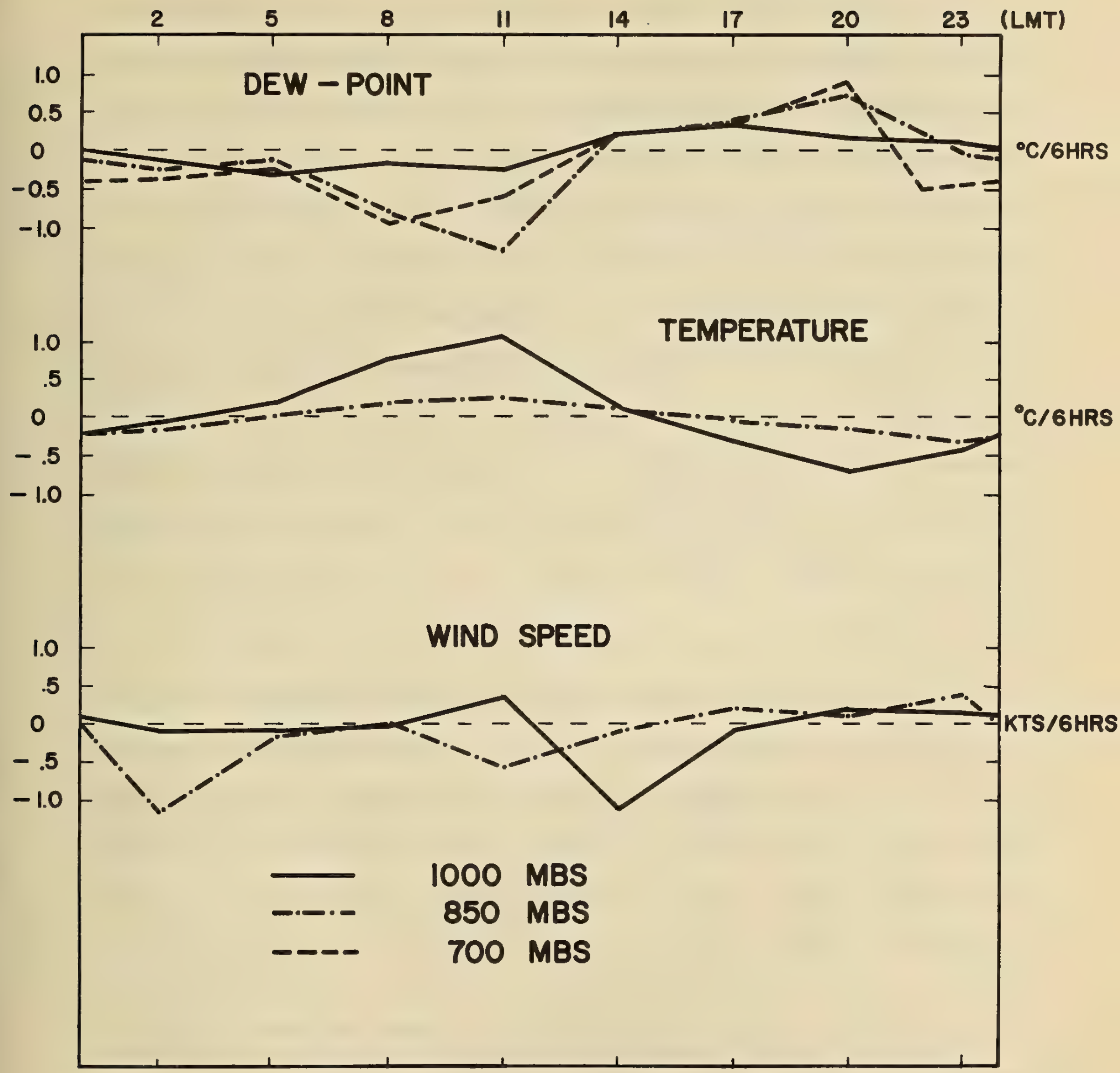


Fig 15. Annual mean diurnal variation of the rate of change of temperature, dew-point, and wind speed (per 6 hrs) in the lower atmosphere over Eniwetok.

The results of this analysis are presented in Fig 15 in graphical form for temperature, dew-point and wind speed. The dew-point variation was analyzed at 1000, 850, and 700 mbs while temperature and wind speed were examined at only the two lower levels. Since the curves depict the trend of the rate of change of the variables, the times of maxima and minima are to be found at the points where the curves cross the zero axis toward negative and toward positive values respectively. For convenience these times have been interpolated from the graphs and listed in Table 5. Also included in the table is an estimate of the range of the diurnal variation at each level, arrived at by integrating the positive and negative portions of each curve separately. Values have been entered for the surface layer (Fig 14) for reference.

TABLE 5

Variation with Height of Diurnal Trends of T and T_d

	Temperature			Dew-Point Temperature			
	Sfc	1000mbs	850mbs	Sfc	1000mbs	850mbs	700mbs
Time of max.	1330	1500	1630	1200	2400	2300	2200
Time of min.	0500	0300	0500	0500	1300	1400	1300
Range (°C)	2.8	1.3	0.5	0.7	0.6	1.2	1.1

The vertical variation of the diurnal temperature curves follows expectation (see e.g. Harris, 1955; Harris et al, 1962). The time of maximum temperature is known to lag with height, and the range should decrease with height. Furthermore the curves demonstrate little radiational influence since radiation errors would tend to increase with height and to induce a temperature maximum at noon. It must be admitted, however, that the observation of a smaller temperature range at 850 mbs (about

5000 ft MSL or 3200 ft above cloud base) than at 1000 mbs does not appear to be in harmony with the hypothesis advanced earlier to explain the nocturnal shower maximum. It was there suggested that the primary nocturnal destabilization occurred in the cloud layer rather than the sub-cloud layer. If this were true it would be expected to result in a relative maximum in diurnal temperature range near the cloud tops (approx. 6300 ft) where radiational effects are largest. This would seem to be necessary if the diurnal change in lapse rate were to have the correct sense at these levels. The question, of course, cannot easily be resolved and requires considerably more information for satisfactory analysis. Data from intermediate levels and a consideration of other aspects of the heat budget (particularly convection and water vapor aspects) are essential.

The diurnal variation of the dew-point temperature (or mixing ratio) is similar at each of the three standard levels; the maximum value is found near midnight and the minimum in early afternoon. The author is unaware of any systematic instrumental errors at work here, but there are two reasons to suspect that this result is unrealistic. Firstly, the 180° shift in phase from the surface to 1000 mbs (approx. 300 ft) cannot be easily accounted for. Secondly, one would expect a noticeable forward tilt of the humidity wave with height through the lower 10,000 ft of the atmosphere in accordance with studies over land. Still, our ignorance of the details of convection processes over the sea and their diurnal variation preclude a positive conclusion. It is conceivable, for example, that the surface maximum results largely from decreased upward transport during mid-day when the lowest air is most stable. The occurrence of a minimum at upper levels would follow through similar reasoning. The reverse distribution would be expected during the night. This reasoning, however,

would lead one to expect the maximum at high levels to be reached at the time of greatest convective activity, i.e. just before sunrise rather than near midnight. Further conjecturing is unwarranted here. A strong need for micro-meteorological measurements over the ocean is certainly evidenced.

Whereas individual monthly mean diurnal trends for temperature and dew-point conform very closely to the annual means portrayed in Fig 15, the wind speeds were highly variable. Little confidence can be placed in the lower curves of Fig 15. For this reason the information on wind speed was not included in Table 5. The analysis nevertheless indicates the absence of strong, organized diurnal variations aloft. The hours showing greatest speed change with time, 0200 and 1400 hrs, are just those hours where the accuracy is poorest (least number of observations). It will be noted, nevertheless, that the 1000 mb curve shows a semi-diurnal variation with maxima at 0100 and 1200 hrs. This is in fair agreement with the surface data. The 850 mb winds show a maximum at 2330 and minimum at 1530 with a range of about 1 kt.

Part III: Synoptic-Scale Disturbances.

Considerable progress has been made in recent years in the elucidation of the nature of perturbations of the trades. The early model of the "easterly wave" disturbance has generally withstood the pressure of synoptic case analysis and theoretical scrutiny. With more detailed observations, however, exceptions to the basic model were certainly to be expected and these have appeared. The question of geographical or seasonal limitations for these types of disturbances has not been explored. Meanwhile, the role of upper-level circulations in the trade regime has been stressed repeatedly, most recently in Pacific case studies made by the Woods Hole Oceanographic Institution (Riehl et al, 1959; Malkus et al, 1961). The subtropical cyclone which lowers its influence into the trade wind regime from upper-levels has been described by Ramage (1962). Tiros satellite observations have showed organized perturbations in the regions (both at high and low levels) to be much more plentiful than previously suspected (Sadler, 1962).

An elementary attempt is made here to investigate the climatological aspects of perturbations in the trade wind regime as exemplified at Eniwetok. It was hoped by so doing to bring out the nature of those disturbances which are most significant in terms of weather production in this portion of the Pacific. For this purpose a machine analysis was made of the $9\frac{1}{2}$ years of hourly surface observations for two types of perturbations: those which disturb the field of wind direction, and those which disturb only the speed field.

Disturbances in surface wind direction

The punched card format at our disposal utilizes a sixteen point compass for specification of surface wind direction. As a first step in the analysis a simple classification of clouds and precipitation versus wind direction was arranged. This is a useful approach here because of the constancy of wind direction; winds from directions other than E and ENE are short-lived and almost invariably represent synoptic-scale disturbances of some kind.

All available observations (over 75,000) were classified according to wind direction, and tabulations were made of 7 quantities: 1) occurrence of precipitation in each of three catagories: light showers, steady rain, and moderate to heavy showers, 2) the amount of low cloud cover, 3) the number of 6-hourly rain reports and the amount of rain recorded (6-hourly observations only).

A seasonal breakdown in such a tabulation is obviously desirable. In terms of the surface wind, the seasons at Eniwetok are fairly clear-cut. From November through June the prevailing direction is ENE, and speeds of less than 5 mph are very infrequent. From July through October the prevailing wind is East and the speeds are noticeably lower; the modal speed in each month is less than 15 mph, and light winds and calms are common. It will be noted that the above seasons correspond closely to the non-typhoon and typhoon seasons in the western Pacific. The 4 month "weak trade" season also corresponds to the period during which the "mid-Pacific trough" becomes firmly established at upper-levels over this region.

The tabulations are summarized in graphical form in Fig 16. The number of occasions with winds from the western semi-circle were so few as to give unreliable percentages, so that these (along with calms) are included under the column heading "other".

Some explanation of the method of representation in Fig 16 is in order. The top three graphs for each season represent the relative frequency of occurrence of each precipitation category under different directions of the surface wind. The "percent occurrence" refers to the proportion of all observations under that particular wind direction which report the particular weather category. Thus, when the wind is from SSE during the winter season there is an 8.7% chance that an airways observation will report a light shower occurring. At the same time the chances of steady rain and of moderate to heavy showers are 10.7% and 5.0% respectively. Thus the probability of rain in any form with SSE winds is 0.24, that is, the percentages are additive.

The graph describing the variation of low cloud amount is straightforward. The graph labeled "rain intensity" refers to the mean amount of rainfall reported under the indicated wind direction whenever <u>measurable rainfall</u> was reported. This graph then portrays rain amounts for "rainy situations" only and for this reason is labeled as intensity. The relative proportion of rainy situations, on the other hand, is given in the top three graphs. The last of the six graphs of each set is a standard histogram presentation showing relative frequency of each category of wind direction.

Certainly the most striking feature of these graphs is the marked

detereoration of weather associated with a surface wind south of East. This effect is more pronounced during the strong trade season. In either season the least chance of precipitation is to be found under ENE flow, but deviations toward southerly winds offer the greatest increase. During the winter, rain is almost 8 times more likely with SSE winds than with the prevailing ENE winds; moderate to heavy showers are about 15 times more likely. These figures are even more arresting when it is realized that some of the southerly winds arose during merely disorganized, light-variable flow.

At the same time it will be noted that southerly excursions of the wind are associated with greater low cloud cover, although the change is small. It seems obvious that the more frequent and heavier precipitation experienced with winds from the SE quadrant are the result of more unstable clouds rather than increased cloud cover. There would probably exist a good correlation between cloud depth and surface wind direction.

Deductions as to the nature of disturbances affecting Eniwetok made on the basis of this climatological evidence suffer from severe limitations. Nevertheless, winds from directions other than E or ENE occur less than 30% of the time and therefore must be largely representative of disturbances. We may conclude that in such disturbances the worst weather occurs under southerly excursions of the wind. Thus the results do not run counter to the standard easterly wave model but should perhaps not be particularized beyond saying that in most disturbances affecting Eniwetok equatorward flow yields near average or slightly better than average weather; poleward flow gives much worse weather. The above points can be made even more convincingly through Fig 20 which depicts

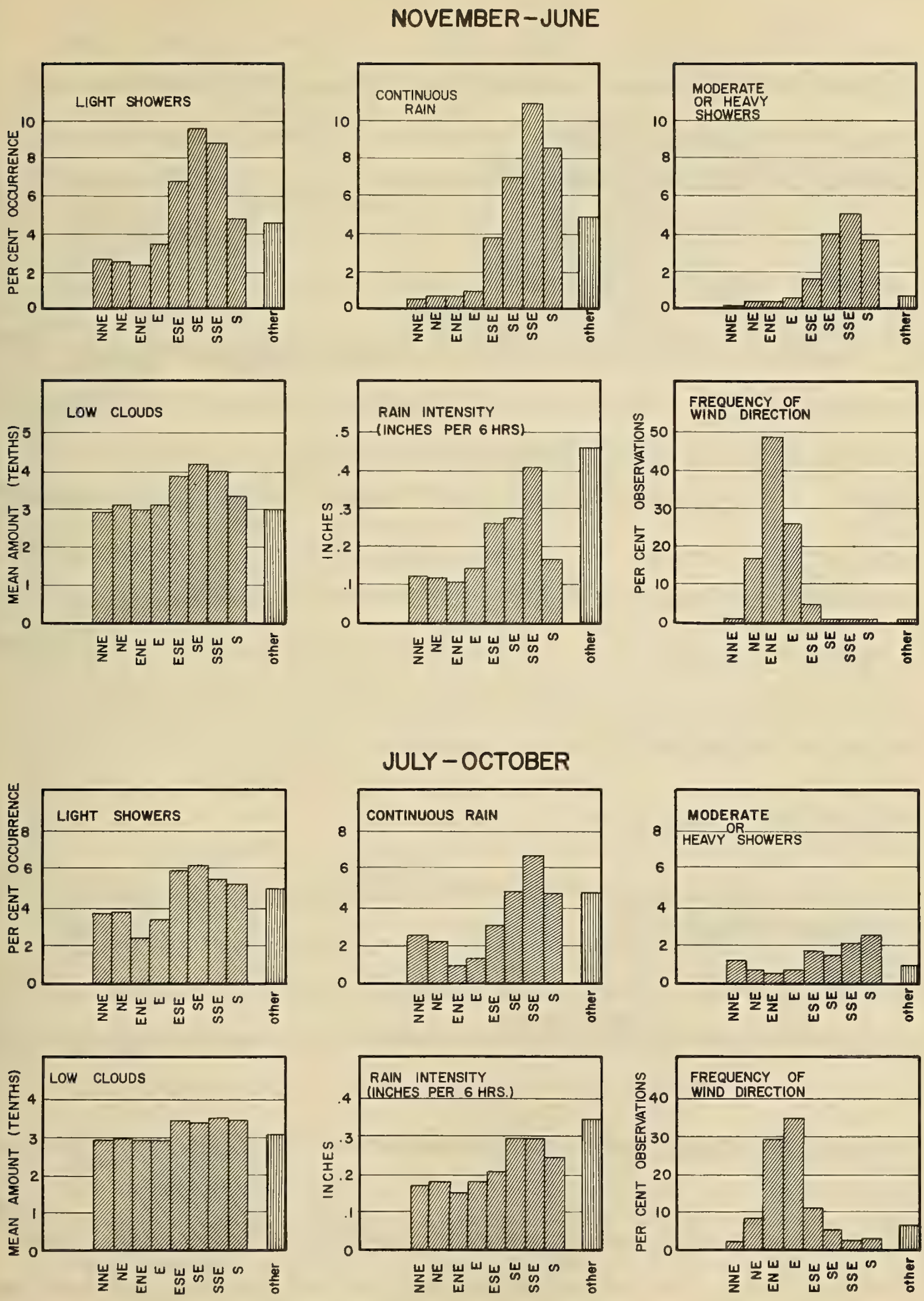


Fig 16. Weather as a function of the direction of the surface wind at Eniwetok within the strong trade wind season and within the season of weak trades. November-June comprise about 50,000 observations, July-October about 25,000.

the distribution of average rain amount with varying wind direction. The curves show the mean rainfall in each direction category expressed as a percentage of the overall mean. Prevailing winds show near normal rain amounts while more northerly winds show somewhat drier conditions. The seasonal difference is exemplified in the two curves.

Whether the disturbances affecting Eniwetok are of some "easterly wave type" or in fact result from the passage of closed vortices to the south can of course not be answered by these data alone. It is also possible that upper-level systems, weakly reflected at the surface, affect these results. Similar climatological studies conducted for other stations in the Marshall Islands and vicinity could very well offer considerable illumination. Lacking this, it may be profitable to examine the correlation of upper-level conditions with surface wind direction for hints of the vertical structure of the disturbances.

Soundings versus surface wind direction

All rawinsonde data cards from Eniwetok from January 1954 to December 1959 (6770 observations) were processed and classified according to the direction of the wind at the 1000 mb level. If the wind speed was less than 5 kts the wind was classified as "calm" and its direction was not used. A tabulation by 10 degree classes of wind direction was then made of dew-point values at 1000, 850, 700, and 600 mbs and of the heights of the 1000, 850, and 700 mb surfaces. The tabulations of these 7 variables were then grouped according to the two seasons described in the previous section. The mean values were computed and expressed as deviations from the overall seasonal mean (for all wind directions). The results are

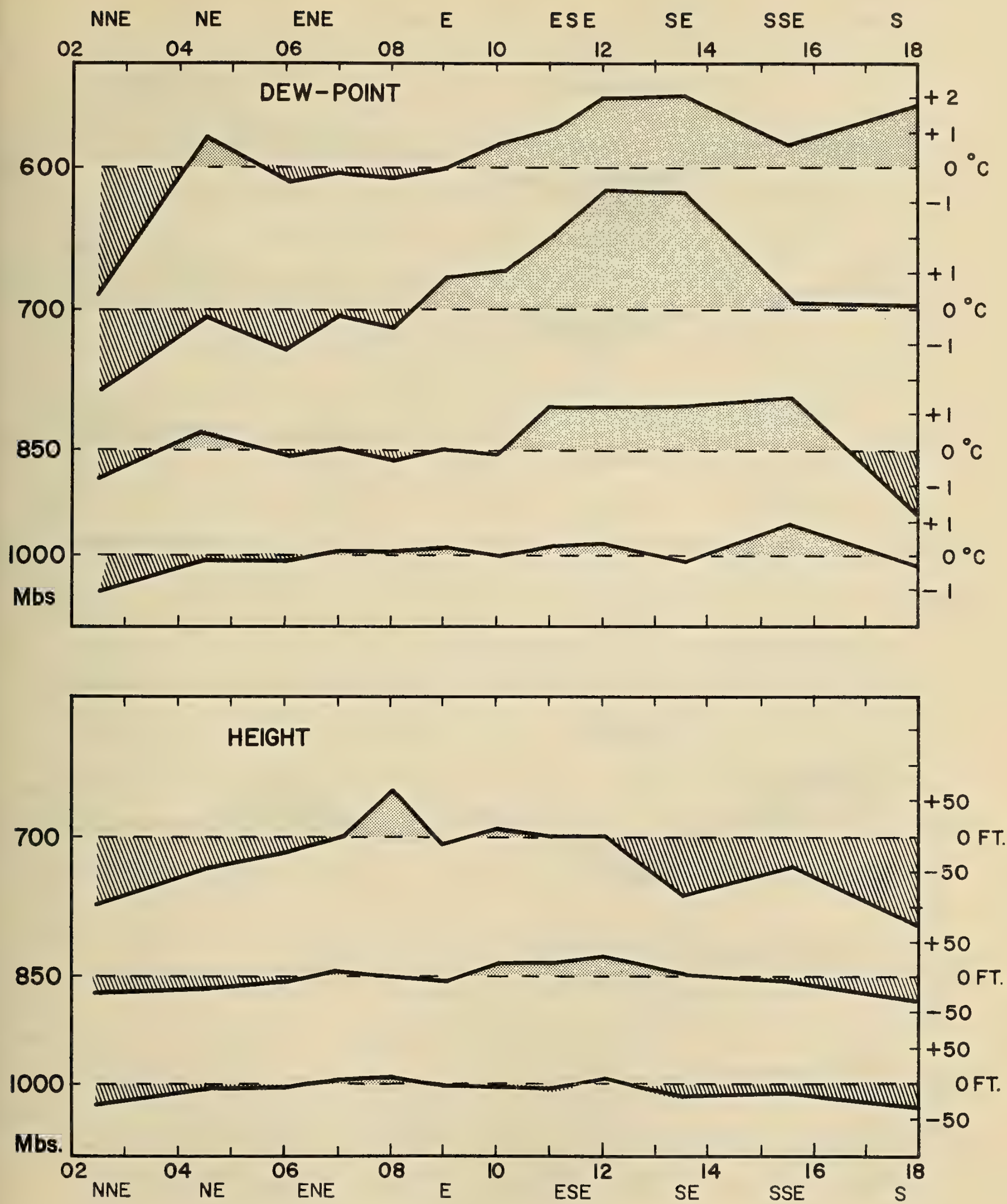


Fig 17. Dew-point and pressure-height in the lower atmosphere over Eniwetok as a function of the direction of the 1000 mb wind for the season of strong trade winds, November-June. Variation at each level is expressed as a mean deviation from the monthly mean at that level.

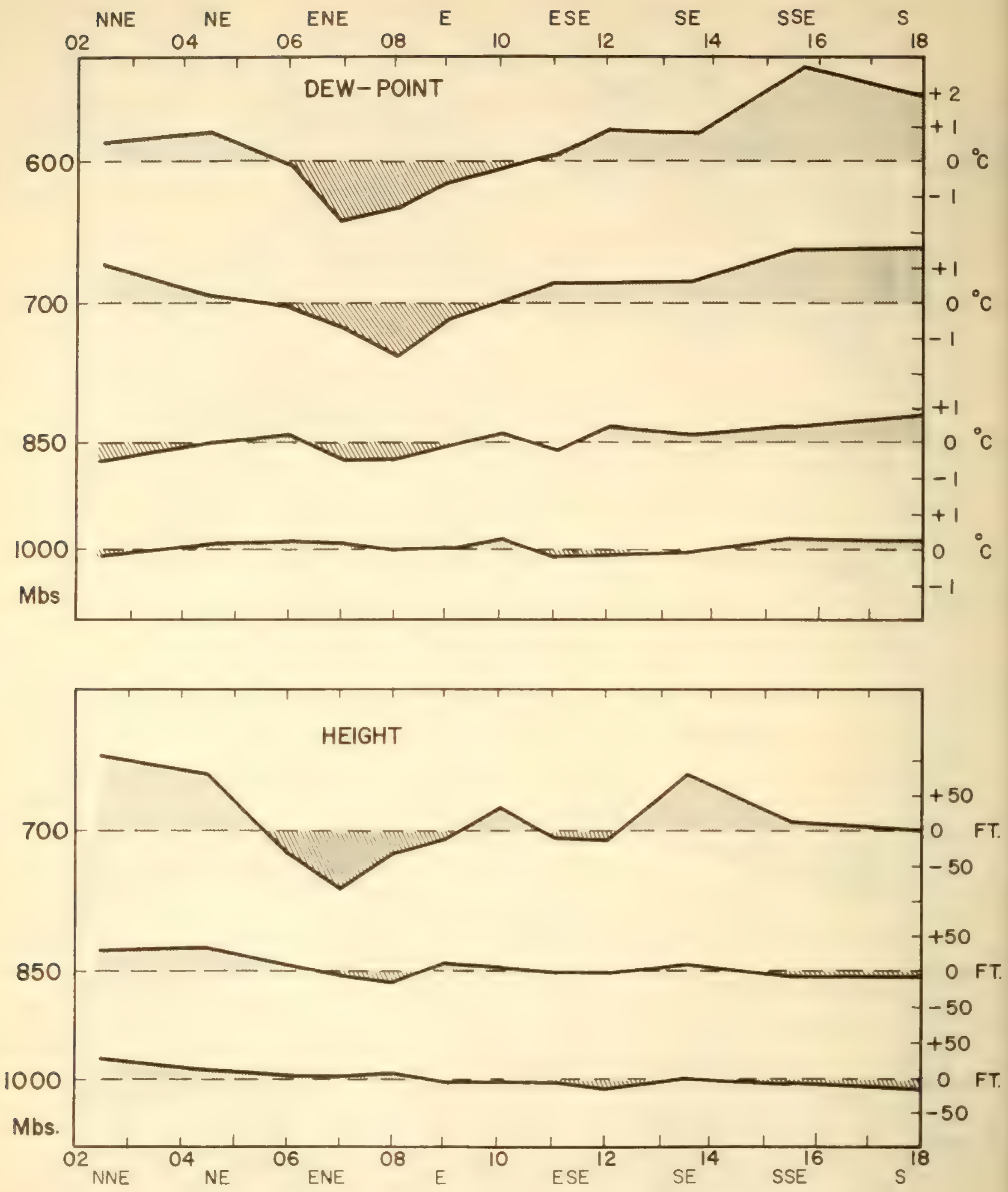


Fig. [illegible]. Same as Fig. [illegible] but referring to the weak trade wind season, July-October.

displayed graphically in Fig 17 and 18.

Mean deviations have been entered on these figures at intervals of 10 degrees for wind directions between 60 and 120 degrees, but fewer observations of other directions made averaging to the points of the 16-point compass appear desirable.

The results of this analysis generally confirm the conclusions drawn in the previous section. The southerly excursions of the wind are accompanied by an increase in moisture aloft and therefore by a lifting of the stable layer limiting low cloud development. It should be noted, however, that the mean dew-point increase is relatively small, reaching a maximum of about 3.5°C at 700 mbs under SE winds during the winter season. This is equivalent to an increase of roughly 10-15% in mean relative humidity at these levels if the temperature change is neglible. Thus, in spite of the very large increase in raininess under these conditions the increase in upper-level moisture is only nominal. Still, the association is unmistakable. Fig 18 further demonstrates that the intensity of these perturbations is smaller during the summer season.

The variations of the height of the pressure surfaces depicted in the lower curves of Fig 17 demonstrate that excursions of the wind away from the prevailing direction are indeed associated with the passage of low pressure systems. The intensity of the "disturbances" appear to increase with height to at least 700 mbs. The height curves in Fig 18 representing the summer situation, on the other hand, fail to provide a convincing correlation with wind direction.

The correlation of upper-level moisture with wind direction is

displayed in Fig 19 in a different form. The percentage of radiosonde ascents which report "motorboating" of the humidity element (relative humidity less than about 12%) is entered for each of the wind directions previously discussed (southerly winds were too scarce in winter to allow a representative percentage computation). The variation is large and convincing only in winter, whereas the mean rain amount versus wind direction (Fig 20) shows a good relationship during both seasons. The seasonal difference in depth of the moist layer is well pointed up by Fig 19. This, of course, has great implications in the problem of typhoon formation in the western Pacific.

In summary, the analysis of dew-point and heights reported by rawinsondes at Eniwetok shows a good correlation with low-level wind direction, particularly during the 6 month "winter season". The data tend to support a conclusion that equatorward flow in disturbances is frequently associated with subsidence and poleward flow with general low-level convergence. There is some evidence that the disturbances are generally most intense at about 700 mbs.

Disturbances in surface wind speed

The resident within the trade wind regime is generally sensitive to slight changes in his environment. Variations in the strength of the trades are quite common and easily perceived. One naturally tries to correlate these changes with cloud and shower activity, and forecasters in these regions frequently have "rules of thumb" built up from such experience. On large or mountainous islands the intensity of sea-breeze effect and of orographic influences will obviously be affected by

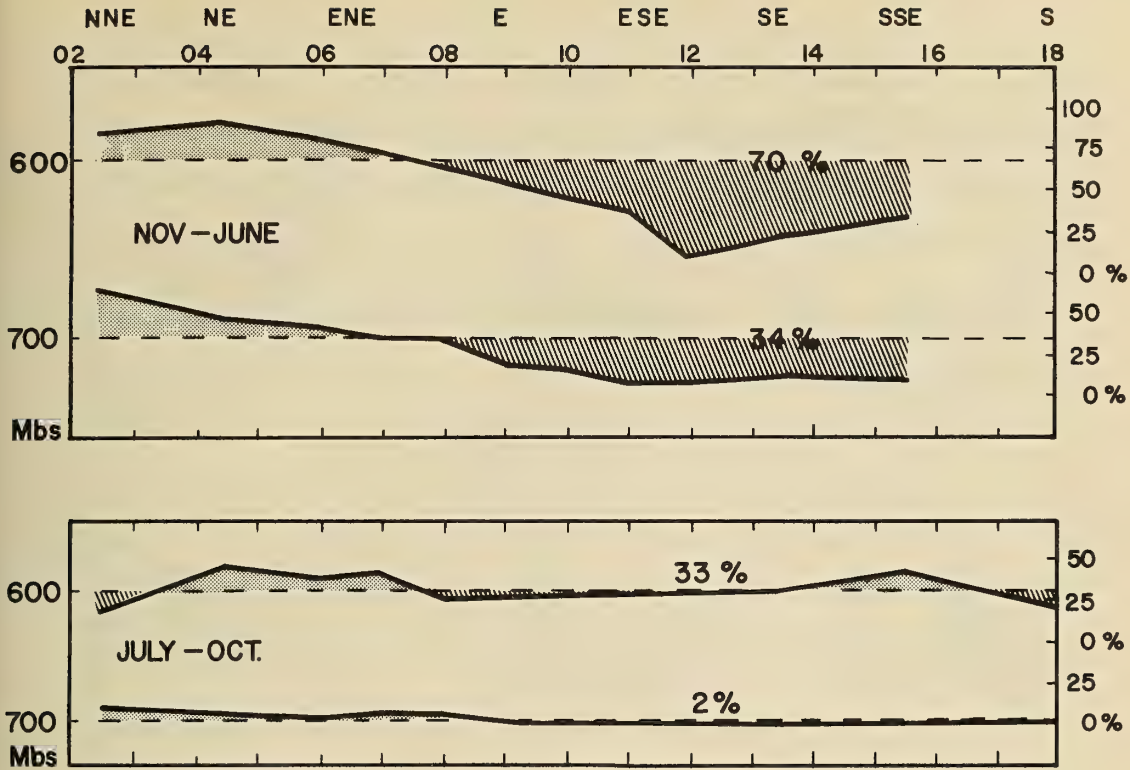


Fig 19. Percent of radiosonde ascents at Eniwetok which report humidity too low to measure (i.e. "motor-boating") at 700 and 600 mb shown as a function of wind direction at 1000 mb. Dashed lines depict the mean percentage for all ascents regardless of wind direction.

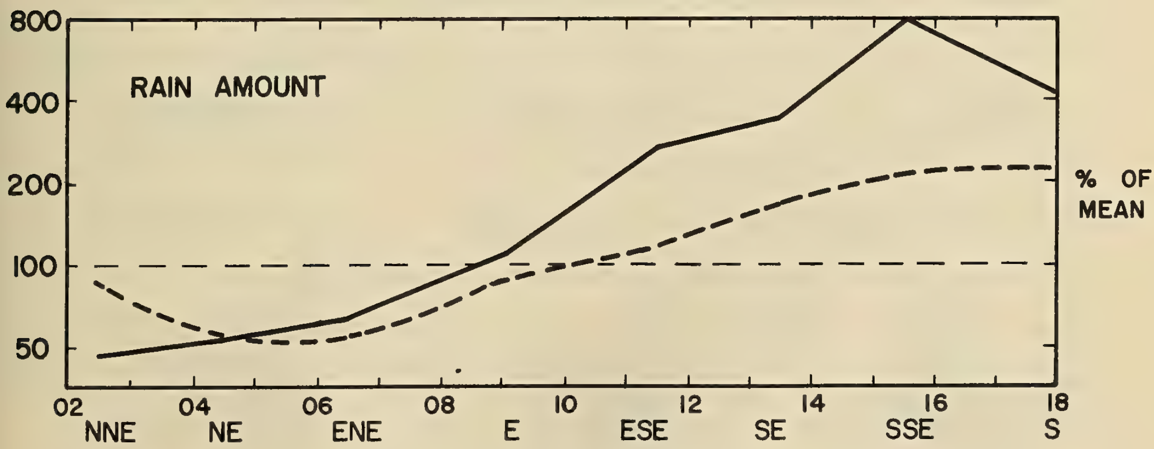


Fig 20. Mean rain amount reported at Eniwetok under varying direction of the surface wind. The means for individual directions (to 16 points) are expressed as a percentage of the grand mean regardless of wind direction. Solid curve refers to the strong trade season (November-June), dashed to the season of weak trades (July-October).

changes in the speed of the prevailing wind. But again the first question to be answered should deal with the nature of these disturbances (if they qualify for that term) over the open oceans, before local effects are introduced.

In order to develop a framework for such a study, Eniwetok surface data were examined for dependence of cloud and rainfall upon the speed of the surface wind, regardless of direction. The results are presented in Fig 21 in the same graphical format used for the wind direction analysis (Fig 16, p 59). The speeds are broken down into six categories of 5 mph width. The histograms showing the frequency distribution of speeds point up the difference upon which the seasonal distinction has been based.

The set of graphs demonstrate once again that the most common wind regime has generally fine weather while excursions away from the mode are associated with worse weather. An interpretation of these excursions as representative of disturbances is not made as readily here as with wind direction. Periods of unusually strong winds definitely seem to be associated with disturbed conditions in either season, but a seasonal distinction appears in the case of abnormally weak flow. Low wind speeds do not give rise to more low cloudiness or rainfall than normal in summer, although they do appear as a definite concomitant to disturbances during the winter season. Individual months were tabulated in all cases to be sure that seasonal summaries were not merely statistical accidents. There was general consistency in all cases.

The seasonal differences in weather versus speed categories may be a reflection of real differences in the nature of disturbances in the two

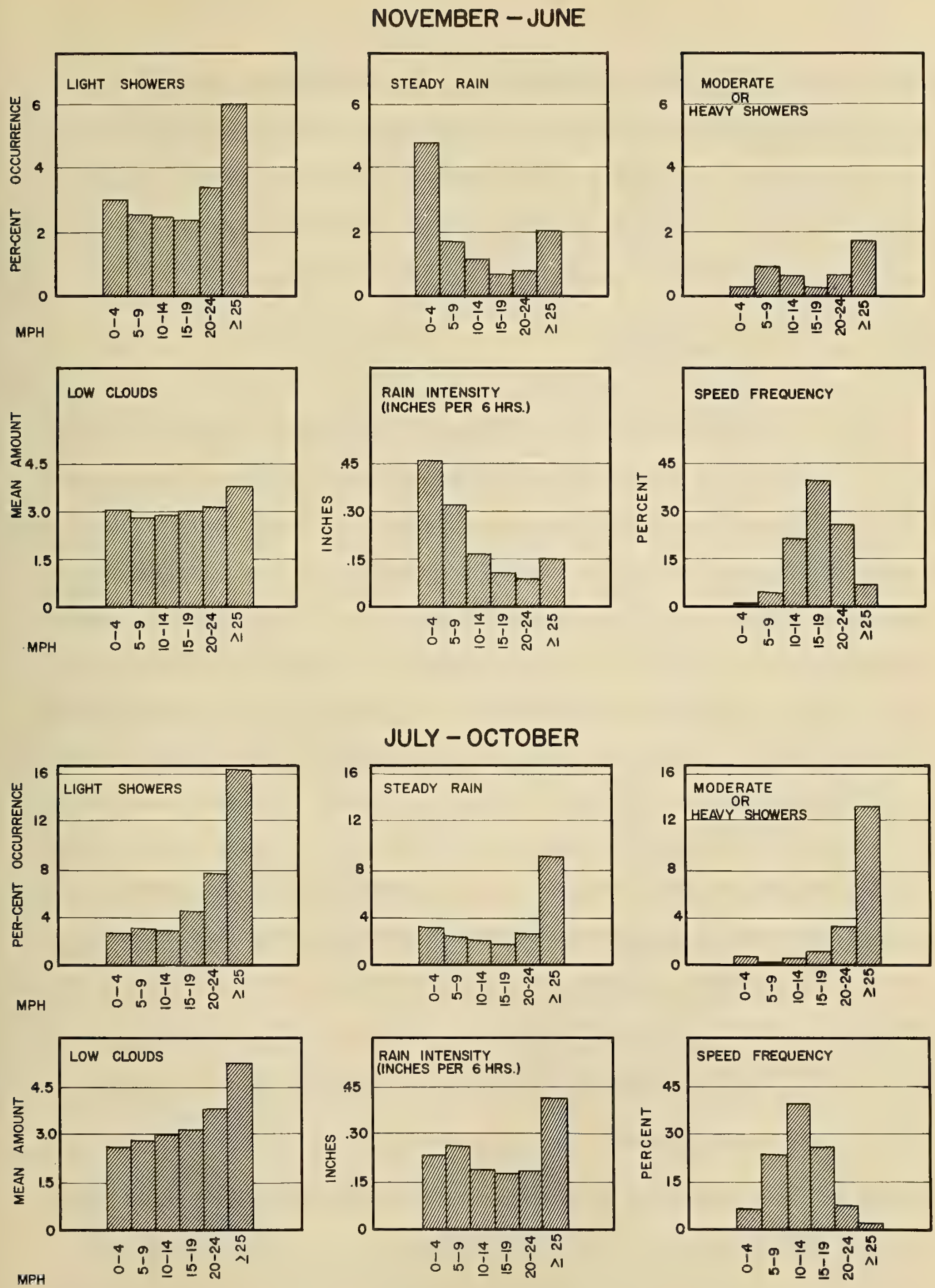


Fig 21. Same as Fig 16 but referring to the speed of the surface wind.

seasons, but conjectures are perhaps inappropriate at this point. It should be noted, however, that in winter, light winds are very unusual and therefore are more likely to represent a highly disturbed condition. Light winds are much more common during the summer and hence strong winds are more likely to be indicative of a synoptic disturbance.

Trade wind maxima and minima

The foregoing analysis made no effort to distinguish between perturbations in speed and direction of the surface wind. Indeed, the two are usually inseparable. Nevertheless, the easterly wave disturbance, for example, affects primarily the direction field in its early stages of development, and it would seem that a case may be made for synoptic scale disturbances whose effect on the trade winds may be largely in the speed distribution (initially at least). An isotach analysis in a typical trade flow is admittedly no easy task, but isolated maxima and minima are common features.

Variations in speed within a straight parallel flow much certainly set up patterns of divergence and convergence which could have important bearing upon weather distribution. The expression for the divergence of a field of motion in terms of distance "s" along a streamline and distance "n" normal to the streamline (positive to the left looking downstream) is

$$\text{Div} = \frac{\partial V}{\partial s} - V\frac{\partial \beta}{\partial n} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

where V is the speed and β is the direction of the wind. If we may limit ourselves to flow which is essentially parallel, the second (difluence) term becomes negligible. Then an isotach maximum with a speed gradient of 6 kts in 300 km would yield Div = 10^{-5}sec^{-1}. This is a respectable

magnitude in terms of vertical motion generation and weather production, provided that the value persists within the same air mass for sufficient time. However, directional difluence amounting to about 25 deg per 300 km could yield the same magnitude of divergence so that care must be taken to rule out the well known tendency for compensation between these terms.

Lacking accurate knowledge of the spatial distribution of the wind speed, the most important parameter to be studied at a fixed point is obviously the rate of change of wind speed with time in cases of negligible directional change. Provided that these isotach centers move nearly in the direction of the wind we should expect increasing winds to be associated with convergence and decreasing speeds with divergence.

The surface data deck for Eniwetok was used to make a survey of the serial change in 6-hourly mean wind speed. It was hoped that such changes would be representative of synoptic scale effects. The 6-hour periods were chosen so that the last hour coincided with the regular synoptic observation during which rain amount is recorded, i.e. 0500, 1100, 1700 and 2300 LMT. Whenever two consecutive 6-hour periods each showed prevailing E or ENE flow (i.e. at least 4 of the 6 observations in each period were from these directions) the mean speeds were computed and compared. It was felt that such a definition of "undisturbed trades" would allow for the occasional minor fluctuations in direction (many times induced by showers) which appear in the data presumably as a result of the short averaging period used in reporting an airways observation.

The difference between the mean speeds in the consecutive 6-hour periods was used as a classification variable against which were

tabulated: 1) mean low cloud amount for the second 6-hour period; 2) serial change in mean low cloud cover from period 1 to period 2; 3) number of hourly rain observations in period 2; 4) rain amount reported for period 2. This tabulation was carried out for individual months of the year and averaged over 1 kt intervals of the serial change in mean wind speed. In making this tabulation it was recognized that heavy showers could themselves influence the wind speed in a given observation and give rise to a correlation which is extraneous to the subject of "synoptic scale" disturbances at which this study was aimed. In order to avoid any local influences of squalls, the magnitude of the wind was not included in the 6-hourly mean computation whenever moderate or heavy rain was reported in present weather.

The tabulation was printed out on a monthly basis, but close examination revealed no annual trend or basis for seasonal distinction. The results were combined and are portrayed in Fig [illegible]. Curve A depicts the variation in mean low cloud amount during the second consecutive 6-hour period associated with the speed change shown as absicca. A positive speed change signifies an increase in surface wind with time. The cloud values are expressed as a percentage of normal low cloud cover (2.93 tenths). It is seen that a good correlation exists between cloud amount and the magnitude of the speed increase. Large decreases in speed, however, also appear to be associated with somewhat more low cloud cover than normal. The variation in cloud amount is admittedly small (little more than one tenth of sky), but as a "measure of disturbance" it is fully as large as those discussed earlier in connection with southerly excursions of the wind direction.

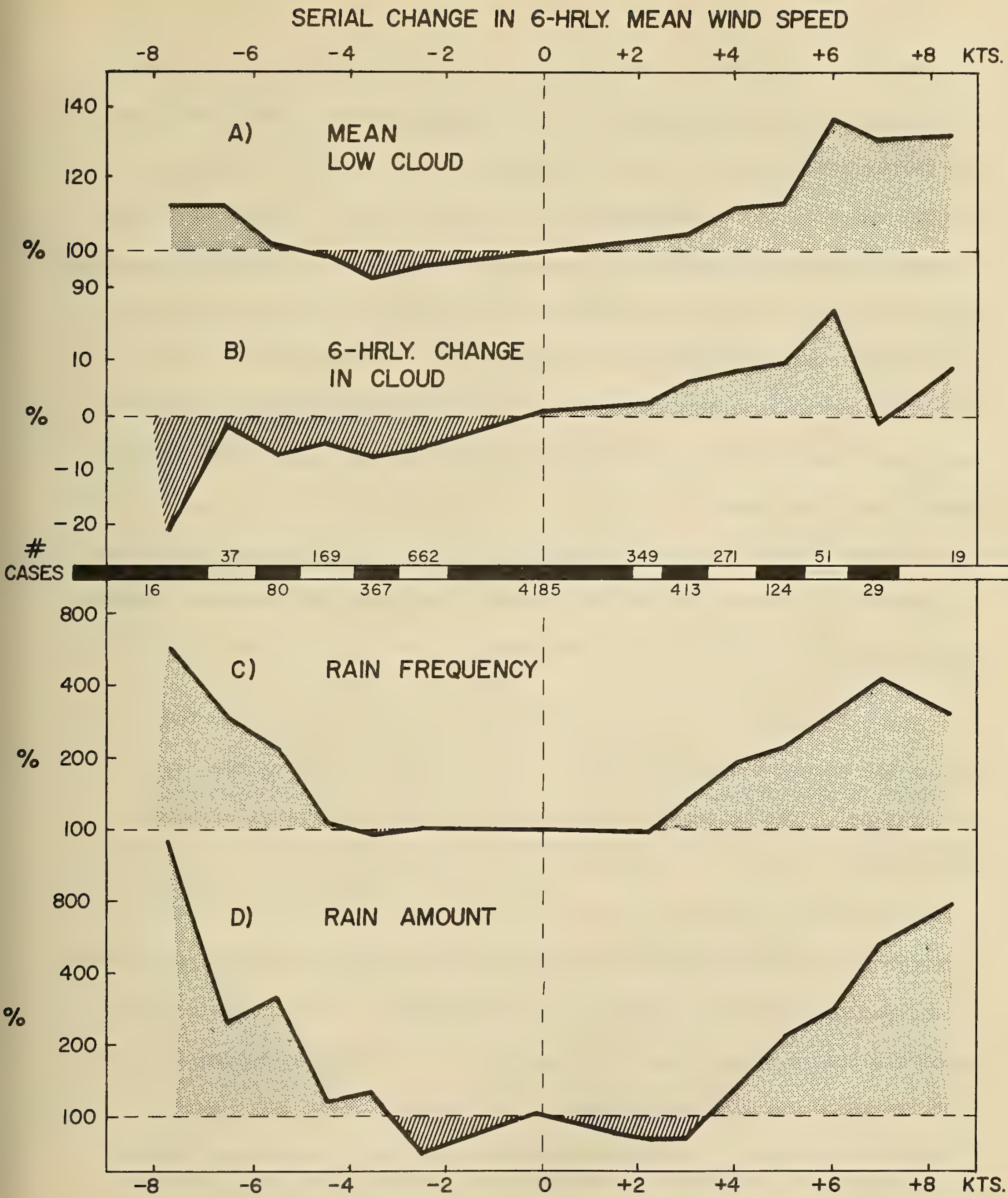


Fig 22. Weather as a function of the serial change in 6-hourly mean wind speed. Curves show mean variations expressed as a percentage of overall mean. Center scale shows averaging interval and the number of observations in each class.

In terms of relating these speed changes to the passage of fields of divergence and convergence, the serial change in low cloud cover from one 6-hour period to the other is of more interest. This is shown in Fig 22, curve B, where the changes are expressed again in terms of percent of normal cover of 2.93 tenths. A good correlation is evidenced indicating perhaps that speed increases are associated with low-level convergence and speed decreases with low-level divergence. However, care must be taken in drawing this conclusion, although it is what one would expect if the sign of the 1st term on the right side of Eq (3) truly controls the sign of the divergence. It would be more generally correct to conclude from Fig 22B that increasing wind speed with time is associated with increasing convergence and that decreasing speed usually indicates decreasing convergence (or increasing divergence).

Curve C shows how the mean number of rain observations reported during the second 6-hour period varies with the magnitude of the "speed disturbance". The values are again expressed as a percentage of normal. Surprisingly, higher rain frequency occurs with both increasing and decreasing speeds. The same sort of picture is seen in curve D which portrays the variation of mean rain amount reported at the end of the second 6-hour period. The mean rainfall for these cases of extreme increase in speed was some 8 times normal; with the cases of extreme slackening of the wind, rainfall was 15 times normal.

In terms of the premise advanced at the beginning of this section, the bad weather associated with slackening wind might appear anomalous. There are several possible explanations for this result, including development of upper-level disturbances, isotach centers which move

upstream, or situations in which the confluence term in Eq (3) is not negligible and actually overbalances the stretching term. Of these three alternatives the last is most reasonable. It seems likely that sharp decreases of wind speed with time are more usually associated with isotach maxima moving away from the station than with approaching speed minima. Under this condition one might expect the region of greatest convergence to be found near the isotach maximum where both components of Eq (3) would probably contribute in the same sense. On the upstream side of the isotach maximum the confluence term would predominate but the convergence would decrease with distance upstream. In other words, the speed (stretching) term tends to predominate ahead of an isotach maxima and the direction (confluence) term is most important behind these features. It is just in such cases as these that the confluence is least likely to show up in the analysis of the wind at a single station. It is quite possible then that the wet periods indicated at the left end of curves C and D of Fig 22 result from situations in which confluence predominated over the stretching effect in spite of the attempt to minimize the former.

The question of the relative frequency of these speed disturbances can be partly answered by referring to the scale in the center of Fig 22. The alternate heavy and open zones demark the extent of the speed scale over which values were averaged to form the curves. The numbers refer to the absolute frequency of these events in an 8 year period at Eniwetok. The extreme cases appear to be very rare (>6 kts in 6 hrs occurs 9 times per year), but it should be stressed that this analysis made no attempt to pick out all such disturbances. No overlapping periods were examined;

a change which largely straddled the static 6-hour periods or extended over more than one period would be suppressed.

It can certainly not be claimed that this brief study has demonstrated the existence of disturbances manifested primarily in the speed field of the lower trades. However, the evidence must be called at least suggestive and would seem to warrant a more concentrated attack on the problem. It is recognized that disturbances such as these must develop curvature within the flow pattern eventually (should they persist), but there appears to be no valid reason to suspect that speed disturbances could not be an important weather phenomenon at low latitudes. A closely related problem in applied tropical meteorology involves the degree to which the sign of the convergence is controlled by confluence in the streamline analysis. Many meteorologists equate the two terms for practical purposes. Further climatological analysis along the lines presented here, but using a network of stations with spatial as well as time derivatives, could throw light on this important problem.

Acknowledgements

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GLOSSARY OF TERMS

Airways observation: coded weather observation reported regularly on the hour by airport weather stations. It is meant to depict weather variables affecting aircraft operations; valid for 3 to 5 minute period ending on the hour.

coalescence mechanism: the process by which a few raindrops grow from a large population of tiny cloud droplets, involving growth by collision. Once a few larger droplets are produced, their greater fall speed enables them to sweep out more and more cloud droplets and thereby grow at an ever-increasing rate.

colloidal stability (of a cloud): a measure of the tendency of cloud droplets to remain in suspension, i.e., not to aggregate into precipitation-sized droplets.

conditional instability: a distribution of temperature with height which allows slight vertical displacements to be stable only on the condition that the air be unsaturated. If "conditionally unstable" air becomes saturated, a parcel of air displaced upward would become buoyant and accelerate upward as a result of the release of latent heat by condensation.

confluence: the opposite of difluence; see difluence.

convergence: the net accumulation of mass of air with time within an arbitrary (small) area on a horizontal map. This air must then be moving either upward or downward at this point since the mass per unit volume (density) remains essentially constant. If the level in question is near sea level, the air must be moving upward. Thus, low-level convergence is associated with rising air and generally bad weather.

difluence: the condition characterized by the tendency of streamlines to move apart. In this case the air tends to flow away from some axis. This does not necessarily lead to a depletion of mass in the region (divergence) since the variation of speed of the flow must also be considered. See divergence equation.

divergence: opposite of convergence. Near the earth's surface it is associated with sinking motion of the air and relatively clear skies.

$\text{Div} = \frac{\partial V}{\partial s} - V\frac{\partial \beta}{\partial n}$: a partial differential equation describing the magnitude of the divergence in terms of the quantities on a horizontal streamline-isotach map. The symbol, ∂, indicates an increment in the value of the following variable. Thus the first term on the right describes the contribution of the rate of change of speed per unit distance along a streamline (stretching effect). The second term is a product of the speed

at a point on a streamline and the rate at which the streamlines change direction per unit distance along a line normal to the streamline at that point. This latter rate of change describes the tendency of the streamlines to diverge and is referred to as the difluence effect. Both of these effects contribute toward divergence, the opposite tendency would lead to convergence.

harmonic analysis: a procedure for expressing the periodic variation of some quantity in terms of the set of oscillations (cosine functions) which best represents the variation. The first cosine curve (first harmonic) covers the fundamental period (here, 24 hours) with one maximum and one minimum. The second cosine curve (second harmonic) has two maxima and two minima in the same period and so forth until the sum of the derived cosine curves exactly duplicates the observed variation. The amplitudes of the "best fit" harmonics generally differ, and their magnitude indicates their relative importance in describing the daily trend of the quantity.

inversion: an atmospheric layer in which the temperature increases with altitude in contrast to the normal "lapse" with height. The "trade wind inversion" is common to the subtropics, particularly in the eastern oceans; its altitude varies from about 2 to 8 thousand feet. Its importance lies in the fact that it forms an effective upper limit to low cloud development. In the trades, then, the air is typically very dry above the inversion. Downstream this inversion becomes higher and less distinct but upper-level dryness tends to persist.

isopleth: line on a graph or chart connecting points of equal value of some quantity which varies over the chart.

isotach: line connecting points of equal wind speed, usually refering to horizontal wind speed on a weather map.

lapse rate: rate at which temperature decreases with height in the atmosphere.

mixing ratio: mass of water vapor per unit mass of dry air, usually expressed in terms of grams of vapor per kilogram of dry air.

motorboating: name given to the condition under which the humidity element in the rawinsonde fails because of very low relative humidity. The term describes the telemetered signal received through a monitoring speaker in such a situation.

rawinsonde: radio transmitting device hung from a buoyant balloon which telemeters to a ground station a nearly continuous record of temperature, humidity, and pressure as it ascends. The instrument is tracked by radio direction-finding equipment or radar in order that horizontal winds can be computed from the balloon drift. If used without wind measuring equipment, the instrument is called a radiosonde.

sensible heat: heat which can be transfered by conduction as a result of a temperature difference (also called enthalpy).

standard pressure level: the reference points in a vertical sounding of the atmosphere at which, by international agreement, the rawinsonde information is always recorded, coded and transmitted. These reference levels are identified by the pressure reading of the rawinsonde.

streamline: line which is parallel to the wind direction at every point along its course. A set of properly spaced streamlines on a horizontal chart thus portrays the instantaneous flow pattern.

subsidence: gentle descending motion, generally through a deep layer of the atmosphere and over a large area.

synoptic: usually applied to the analysis of large numbers of simultaneous weather observations. Hence, synoptic features are those depicted by weather maps --- weather systems on a scale of the order of 500 km or more.

thermal: more or less distinct mass of less dense (warmer) air which rises under buoyancy forces -- may or may not reach condensation level and continue rising as a visible "cloud thermal".

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ATOLL RESEARCH BULLETIN

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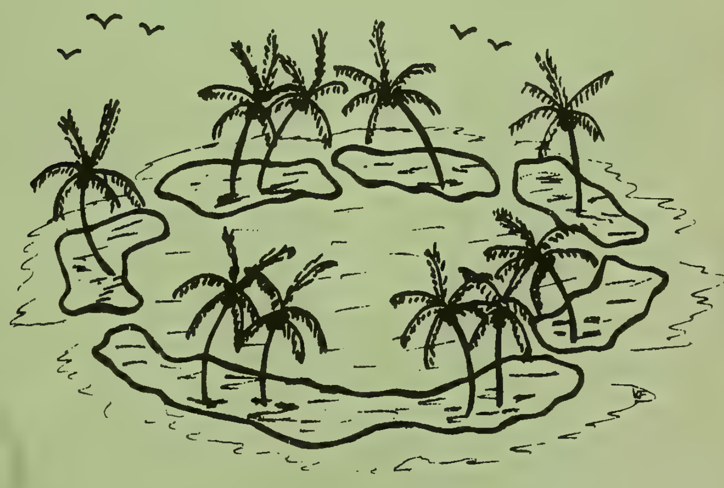

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Washington, D. C., U.S.A.

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ACKNOWLEDGMENT

It is a pleasure to commend the far-sighted policy of the Office of Naval Research, with its emphasis on basic research, as a result of which a grant has made possible the continuation of the Coral Atoll Program of the Pacific Science Board.

It is of interest to note, historically, that much of the fundamental information on atolls of the Pacific was gathered by the U. S. Navy's South Pacific Exploring Expedition, over one hundred years ago, under the command of Captain Charles Wilkes. The continuing nature of such scientific interest by the Navy is shown by the support for the Pacific Science Board's research programs during the past fifteen years.

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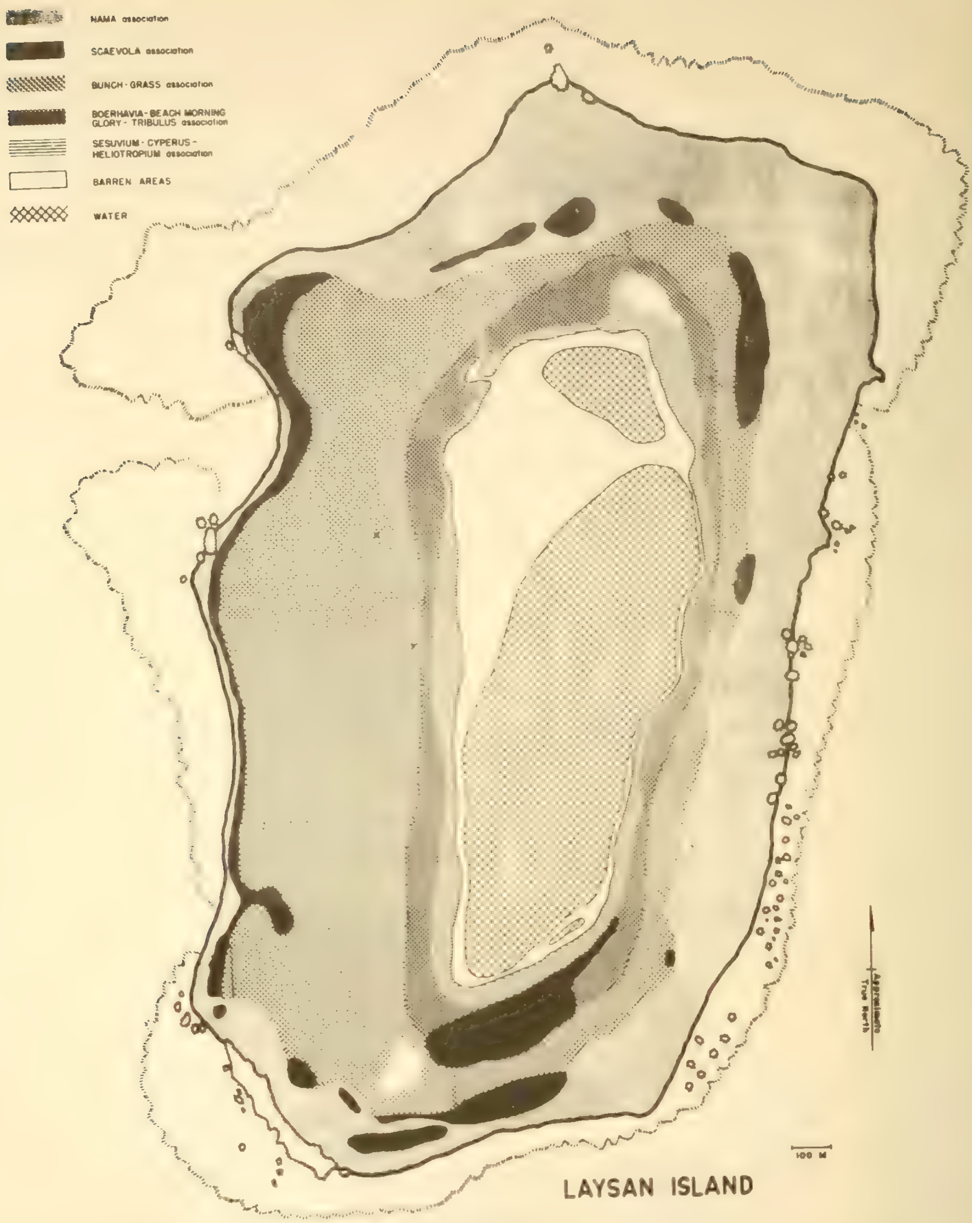

Fig. 1. Vegetation map of Laysan Island, based primarily on data collected in September 1961. The water level in the lake is known to vary somewhat, and at times the large "barren area" in the center of the island is completely under water.

The flora and vegetation of Laysan Island

by

Charles H. Lamoureux *

Laysan Island, one of the Leeward Hawaiian Islands, is located about 790 nautical miles northwest of Honolulu at 25° 42' 14" North latitude, 171° 44' 6" West longitude. The island is about one and three/quarters miles in length and one mile wide. It is a low coral island. Most of its surface is composed of coral sand, with patches of coral reef and beachrock near the shore. The island is used as a nesting area by various sea birds, and there were formerly large deposits of guano present. The center of the island is occupied by a salt-water lake. The west, north, and south rims of the island reach heights of 30 to 40 feet before sloping downward toward the central lake, but the south rim is only about 10 feet above sea level.

Laysan has long been known to naturalists, not only as a major breeding ground for sea birds, but also as the home of five endemic land birds and five endemic plants. The history of Laysan has been described at length in several other publications (Christophersen and Caum, 1931; Bryan, 1942; Bailey, 1956) and will only be summarized briefly here.

The first recorded discovery of the island was made in 1828 by Captain Stanikowitch of the Moller. In 1857 Laysan was annexed to the Kingdom of Hawaii (it is now part of the State of Hawaii and the City and County of Honolulu). In 1892 guano digging operations began on Laysan. In 1903, just before guano digging ceased, rabbits were introduced to Laysan. The rabbits were typically prolific, and by the time the Tanager expedition visited Laysan in 1923 most of the plants and many of the birds had disappeared. With the disappearance of the plants the rabbit population became depleted by starvation. The Tanager expedition killed the remaining rabbits and planted seeds and cuttings of many plant species, and additional plantings were made by G. P. Wilder in 1930. There have been no published reports on the recovery of the vegetation since the removal of the rabbits and the replanting of the island.

Through the courtesy of Dr. Harold J. Coolidge and the United States Coast Guard I was able to visit Laysan on September 4-10, 1961. Thanks are also due George Butler, M.D.F. Udvardy, Richard Warner, and David Woodside, all of whom had previously visited the island and were able to provide me with useful information about it.

FLORA

The flora of Laysan, like that of most low oceanic islands, contains relatively few species. A total of 38 species of vascular plants, of which not more than 27 were native, have been recorded at

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various times from the island. In 1961 there were 24 species growing on Laysan of which not more than 16 were native.

Early visitors to the island, Isenbeck in 1828 and Paty in 1857, provided little specific information on the flora other than noting the presence of a small species of fan palm (Pritchardia sp.). Captain N. C. Brooks of the Gambia collected "25 varieties of plants, some of them splendid flowering shrubs" in 1859. Unfortunately his collections have disappeared, and the identifications, if made, were never published. In 1891 George C. Munro spent 10 days on Laysan. His notes (1942) provide descriptions sufficiently detailed that a few plants can be recognized: Eragrostis variabilis, Sesuvium portulacastrum, Sicyos sp., Capparis sandwichiana, Tribulus cistoides, Ipomoea pes-caprae, and Pritchardia sp. Munro noted two palms still standing and the stumps of several more. When Schauinsland visited Laysan in 1896-97 the palm had become extinct. Schauinsland made the first collection of Laysan plants which is available to science. Part of his collection is preserved in the Bernice P. Bishop Museum. W. K. Fisher's collections, made in May 1902, were determined by W. E. Safford and published by Fisher (1903a). Later collections, all at the Bishop Museum, were made by W. A. Bryan in April 1903 and April 1911, E. L. Caum in April 1923, G. P. Wilder in August 1930, G. D. Butler, Jr. in April and July 1959, C. W. Daniel in July 1959, and C. H. Lamoureux in September 1961.

Although detailed treatments of the flora of Laysan have been presented by Bitter (1900) and Christophersen and Caum (1931), there have been significant changes in the composition of the flora in recent years. Thus, it seems advisable to present a list of the species which have been recorded from Laysan, to include in parentheses the synonyms which have been used in other treatments of the Laysan flora, and to indicate the dates at which each species was observed or collected. Species growing on Laysan in September 1961 are preceded by an asterisk.

GRAMINEAE -- Grass family

Cenchrus agrimonioides var. laysanensis F. Br. (Cenchrus calyculatus Cav.). This unusual sand-bur was collected on Laysan between 1896 and 1911, but became extinct there by 1923. It still survives on Kure in limited numbers.

* Cynodon dactylon (L.) Pers. Bermuda grass was collected first in 1903, and was probably introduced during the guano digging operations. It was not found in 1911 or 1923, but is present in 1930, 1959, and 1961 collections. It may have been replanted in 1923.

* Eragrostis variabilis (Gaud.). Steud. (Eragrostis hawaiiensis Hillebr.). This bunch grass, noted by Munro in 1891, was described by Schauinsland as the most common plant on the island in 1896. It was present in all collections until 1923, at which time no living plants were observed. Rhizomes and seeds were planted in 1923, and the species has been represented in all later collections. In 1961 this grass was again abundant.

Lepturus repens (Forst.) R. Br. This grass, characteristic of strand areas throughout much of the tropical Pacific, was collected on Laysan only in 1896 and 1903.

Sporobolus virginicus (L.) Kunth. Another beach grass, collected only in 1896 and 1903.

CYPERACEAE — Sedge family

* Cyperus pennatiformis var. bryanii Kükenthal (Cyperus canescens Vahl). A striking sedge, endemic to Laysan, was collected between 1896 and 1911. Although not observed in 1923, it was present in all collections since 1930.

* Fimbristylis cymosa R. Br. First collected in 1930, this sedge was apparently planted on Laysan by the Tanager expedition in 1923. In 1961 it was distributed widely over the island.

PALMAE — Palm family.

* Cocos nucifera L. Coconuts were first planted on Laysan by the guano workers. Some trees survived at least until 1923 but died before 1959. Several young trees, planted in 1959, appeared to be thriving in 1961.

Pritchardia sp. Specimens of a small fan palm, probably Pritchardia, were seen on Laysan by Isenbeck in 1828, and were also observed by Paty in 1857, Brooke and Brooks in 1859, and Munro in 1891. The palm had become extinct by 1896, at which time Schauinsland found only dead stumps. No specimens of this palm are known to exist in any herbaria. The only permanent record is a photograph taken at some time between 1891 and 1896 by an unknown photographer, which shows two living trees and the stumps of others. This photograph, which was reproduced by Christophersen and Caum (1931), does not reveal sufficient detail to permit identification. It is generally agreed that the palm was a Pritchardia, of which one species, P. remota, occurs on Nihoa. The Hawaiian species of Pritchardia are of extremely local distribution, no species being found on more than one island. Although Rock (Beccari and Rock, 1921) suggests that the Laysan plant was also P. remota, George C. Munro (personal communication, 1961), who observed both the Nihoa and Laysan palms, is of the opinion that they were of different species, a conclusion also reached by Christophersen and Caum (1931).

CASUARINACEAE — Ironwood family.

* Casuarina equisetifolia L. One ironwood tree was growing on the island in 1923 and showed signs of rabbit damage (Wetmore, 1925). The single tree still on Laysan in 1961 is probably the same tree.

SANTALACEAE -- Sandalwood family

Santalum cuneatum var. laysanicum Rock (S. freycinetianum Gaud.). The Laysan sandalwood, first collected in 1896, was still living in 1923 when "many of the stumps were seen to be alive and trying to sprout, in spite of their being kept trimmed clean by the rabbits" (Christophersen and Caum, 1931). Since 1923, however, the sandalwood has not been collected.

CHENOPODIACEAE -- Goosefoot family

Chenopodium oahuense (Meyen) Aellen (C. sandwicheum Moq.). The aweoweo, which in 1896 was exceeded in abundance only by Eragrostis, disappeared from Laysan between 1903 and 1911.

AMARANTHACEAE -- Pigweed family

Amaranthus viridis L. (Euxolus viridis (L.) Moq.). This species was probably introduced to Laysan by the guano workers, and was collected between 1896 and 1903.

Achyranthes splendens var. reflexa Hillebr. A native shrub first collected in 1896 which apparently became extinct between 1903 and 1911.

NYCTAGINACEAE -- Four o'clock family

* Boerhavia diffusa L. (B. tetrandra Forst.). Present in all collections of plants from Laysan (except 1923, when all plants observed appeared to be dead), Boerhavia formed one of the major elements of the vegetation in 1961.

AIZOACEAE -- Mesembryanthemum family

* Sesuvium portulacastrum L. The akulikuli was the only plant native to Laysan that was at all abundant in 1923. Although not collected in 1930, it must have been present then, and was found to be growing well in 1959 and 1961.

PORTULACACEAE -- Purslane family

* Portulaca lutea Sol. (P. oleracea L.). Present in all collections except 1930.

* Portulaca oleracea L. Collected only in 1959 and 1961, this species is apparently a recent introduction to Laysan. Schauinsland's specimens, called P. oleracea by Bitter (1900), are actually P. lutea.

CRUCIFERAE -- Mustard family

Lepidium o-waihiense C. & S. Collected only by Schauinsland in 1896, who observed only a single plant.

CAPPARIDACEAE -- Caper family

* Capparis sandwichiana DC. The puapilo was probably one of the "splendid flowering shrubs" noted by Captain Brooks in 1859. It was also observed by Munro in 1891, and was represented in collections between 1896 and 1903. It had disappeared by 1911 and was not found in 1923, but was collected again in 1930, 1959, and 1961.

ZYGOPHYLLACEAE -- Caltrop family

* Tribulus cistoides L. Represented in all collections from 1896 to 1961.

MALVACEAE -- Mallow family

Hibiscus tiliaceus L. The hau was evidently planted on Laysan by the guano workers, and three trees were observed in 1923 growing near the old buildings. It has not been found since 1923.

CONVOLVULACEAE -- Morning glory family

* Ipomoea indica (Burm.) Merr. (I. insularis Steud.). This morning glory was collected between 1896 and 1903, and then not again until 1959 and 1961.

* Ipomoea pes-caprae (L.) Sw. The beach morning glory, first noted by Munro in 1891, was also not collected between 1903 and 1959.

HYDROPHYLLACEAE -- Waterleaf family

* Nama sandwicensis var. laysanicum Brand. Nama has been represented in all Laysan collections except that of 1923.

BORAGINACEAE -- Borage family

* Heliotropium curassavicum L. The seaside heliotrope apparently disappeared from Laysan between 1903 and 1911, but was present again in 1930, 1959, and 1961.

* Messerschmidia argentea (L. f.) Johnston. The tree heliotrope was collected on Laysan for the first time in 1961 when only a single plant was found.

LABIATAE -- Mint family

Phyllostegia variabilis Bitter. This species became extinct on Laysan between 1903 and 1911. It may still survive on Kure.

SOLANACEAE -- Nightshade family

* *Nicotiana tabacum* L. Tobacco was probably introduced by the guano workers, and is present in all collections from 1911 to 1961. In 1923 it appeared to be thriving although most other plants had disappeared, probably because it was not palatable to the rabbits.

Solanum nelsoni Dunal (*S. laysanense* Bitter). This small native *Solanum* disappeared from Laysan between 1903 and 1911.

Solanum nodiflorum Jacq. The black nightshade was found on Laysan only in 1930.

CUCURBITACEAE -- Squash family

* *Sicyos hispidus* Hillebr. Collected from 1896 to 1911 and again from 1930 to 1961.

* *Sicyos* sp. Collected in 1903, 1911, and 1961 only.

GOODENIACEAE -- Goodenia family

* *Scaevola taccada* (Gaertn.) Roxb. (*S. koenigii* Vahl, *S. lobelia* L., *S. frutescens* (Miller) Krause). Represented in all collections from Laysan.

COMPOSITAE -- Composite family

Lipochaeta integrifolia (Nutt.) Gray. The nehe was collected in 1896 and 1903, but has not since been found on Laysan.

* *Pluchea indica* (L.) Less. A recent introduction, collected only in 1959 and 1961.

In addition to the plants listed above, which are known to have grown on Laysan, other species have been planted there. In 1923 and again in 1930 G. P. Wilder planted seeds and cuttings of various species in an attempt to revegetate Laysan after its devastation by rabbits. Although complete records are not available, it is known that *Casuarina equisetifolia*, *Calophyllum inophyllum*, *Pritchardia* sp., *Coccoloba uvifera*, *Thespesia populnea*, *Hematoxylon campechianum*, *Cocos nucifera*, various Hawaiian lobelias, *Scaevola taccada*, *Eragrostis variabilis*, and *Lepturus repens* were planted (Gregory, 1924, 1931; Christophersen and Caum, 1931). Of these only *Scaevola* and *Eragrostis* were successful - it is not even certain that these were, since both plants were already on the island

and viable seeds of both species were probably already in the soil. It is quite probable, however, that in 1923 seeds of Fimbristylis cymosa were planted, and this introduction was successful.

Seeds of several species have been found on Laysan beaches although the plants do not grow on the island. These seeds have probably drifted ashore and are either inviable because of long exposure to sea water or have not met proper conditions for germination. Species known only from seeds are Aleurites moluccana, the candlenut, and four species of leguminous vines: Entada scandens, Mucuna gigantea, Dioclea altissima, and Caesalpinia crista (Christophersen and Caum, 1931).

Heller (1897) seems to have been mistaken when he indicated that Gossypium tomentosum, the Hawaiian cotton, was to be found on Laysan. There are no records of the occurrence of this plant on Laysan, and Heller apparently never visited the island.

Of the 38 species that have grown on Laysan, 10 have evidently been introduced by man, either intentionally or otherwise. These are:

Cynodon dactylon
Cocus nucifera
Casuarina equisetifolia
Amaranthus viridis
Portulaca oleracea
Hibiscus tiliaceus
Messerschmidia argentea
Nicotiana tabacum
Solanum nodiflorum
Pluchea indica

It is highly probable that another species, Fimbristylis cymosa, which is native to the main Hawaiian Islands, was also introduced intentionally in 1923.

Among the 27 remaining species are 11 which have a rather wide distribution on the islands of the Pacific. These are:

Lepturus repens
Sporobolus virginicus
Cyperus laevigatus
Boerhavia diffusa
Sesuvium portulacastrum
Portulaca lutea
Tribulus cistoides
Ipomoea indica
Ipomoea pes-caprae
Heliotropium curassavicum
Scaevola taccada

Nine species are endemic to the Hawaiian Islands, but are found on both the main islands and the leeward islands:

Eragrostis variabilis
Chenopodium oahuense
Achyranthes splendens var. *reflexa*
Lepidium o-waihiense
Capparis sandwichiana
Solanum nelsoni
Sicyos hispidus
Sicyos microcarpus
Lipochaeta integrifolia

Three species or varieties are restricted to the leeward islands:

Cenchrus agrimonioides var. *laysanensis*
Nama sandwicense var. *laysanicum*
Phyllostegia variabilis

Four species or varieties occur only on Laysan:

Cyperus pennatiformis var. *bryanii*
Pritchardia sp.
Santalum cuneatum var. *laysanicum*
Sicyos sp.

The flora of Laysan has a distinctly Hawaiian character. Of the 27 species or varieties native to the island, 16 or 59% are endemic to the Hawaiian Islands; of these 16, nine are distributed throughout the chain, three are restricted to the leeward islands but are found on more than one island, and four are restricted to Laysan. The 24 species found on Laysan in 1961 represent eight introduced species, nine species of wide distribution in the Pacific, four species endemic to the entire Hawaiian Islands, one species restricted to the leeward islands, and two species restricted to Laysan.

VEGETATION

Early visitors to Laysan described the rather dense vegetation covering the island (cf. Christophersen and Caum, 1931; Bryan, 1942). Isenbeck in 1828 noted that most of the island was covered with a bushy grass (*Eragrostis*). In places were short shrubs (probably *Chenopodium* and *Scaevola*), between which were a few dwarfed fan palms (*Pritchardia*).

Paty described the island in 1857 as covered with "beach grass" (presumably *Eragrostis*) and having half a dozen palm trees. Brooks in 1859 noted "a luxuriant growth of shrubs" and five palm trees. Munro in 1891 found the island "to be covered a good deal by vegetation" (personal communication, 1961) consisting of a tussock grass (*Eragrostis*) and some tangled scrub (probably *Chenopodium* and *Scaevola*). The scrub was more abundant at the north end of the island. He found the beds of guano covered with a carpet of "iceplant" (probably *Sesuvium*), and a

carpet of "iceplant and other creepers" fringing the lake. Munro also noted two *Pritchardia* trees and the stumps of several more.

Schauinsland (1899) provided a detailed description of the vegetation as it was in 1896. Although the *Pritchardia* had become extinct by this time (Schauinsland found only dead stumps, but estimated the former number of trees at several hundred), Laysan had just begun to feel the influence of man and was still in a relatively unspoiled state. Only one (*Amaranthus viridis*) of the 26 plant species Schauinsland found was introduced by man. On the higher parts of the beaches he noted that *Lepturus* and *Sporobolus* were abundant. In this region also were plants of *Phyllostegia*, *Nama*, *Portulaca*, and *Santalum*. At the northwest end of the island *Santalum* was especially abundant.

Just above the beach, on the seaward slope, was a region of *Scaevola* shrubs, among which were growing *Solanum* and both species of *Ipomoea*. In this region, on the west side of the island, were several shrubs of *Capparis*, and at one place on the northwest side of the island was a stand of *Achyranthes* about 100 meters in diameter.

Inland of the *Scaevola* was a zone dominated by *Eragrostis* which covered most of the island. The *Eragrostis* formed clumps among which were found plants of *Cenchrus*, *Tribulus*, *Boerhavia*, and *Ipomoea indica*. The shrubby *Chenopodium* was widely distributed throughout this zone and was apparently especially well developed on the lower, inner slopes. Toward the inner part of this zone *Cyperus pennatiformis* was occasionally found. In the transition region between *Eragrostis* and the *Sesuvium* association around the lake, *Lipochaeta* was present.

The band around the lake was composed predominantly of *Sesuvium*, *Heliotropium*, and *Cyperus laevigatus*. Mixed with these were *Sicyos* spp., *Cyperus pennatiformis*, and *Amaranthus*.

Schauinsland further noted that the vegetation of the western half of the island was more luxuriant and was composed of more species than that of the eastern half.

In 1902 Fisher (1903a,b) noted essentially the same zonation of vegetation described by Schauinsland, but added that the band around the lake also contained large numbers of *Portulaca lutea* plants. Conditions must have been similar at the time of W. A. Bryan's visit in 1903. He collected all but two of the species found by Schauinsland (*Lepidium* and *Sicyos microcarpus*), and added only two new species (*Cynodon* and *Sicyos* sp.). At about this time, however, rabbits were introduced to Laysan and extensive changes in the vegetation began. When Bryan made his next visit to the island, in 1911, 13 of the 26 species that he collected in 1903 had disappeared. Bryan predicted at this time (Dill and Bryan, 1912) that even more species would disappear unless drastic measures were taken.

Unfortunately Bryan's advice was not accepted, and when the members of the Tanager Expedition visited Laysan in 1923, they found a veritable wasteland. Only four native plant species were still growing (*Sesuvium*, *Portulaca lutea*, *Tribulus*, and *Scaevola*). Living stumps of *Santalum*

were observed (Christophersen and Caum, 1931), but they evidently died soon thereafter. Only dead plants of Boerhavia could be found. Four introduced species had survived -- one ironwood, two coconuts, and three hau trees, in addition to several tobacco plants which were apparently so unpalatable that their number was increasing. The members of the Tanager expedition exterminated the rabbits and planted seeds and cuttings of many species in an attempt to revegetate the island.

With the disappearance of the rabbits, the vegetation started to return to Laysan. In 1930 G. P. Wilder collected 13 species, 9 of which were native. The Templeton Crocker expedition visited the island in December 1936 and "reported that conditions, while not yet back to pre-poacher and pre-rabbit optimum, were greatly improved" (Bryan, 1942). Aerial photographs made in May 1949 (Bailey, 1956) reveal a dense cover of vegetation over much of the island and are quite similar to aerial photographs made in July 1961.

In 1959 a preliminary study of the vegetation was made along two transects from the sea to the lake by Dr. M. D. F. Udvardy. In 1961 this study was extended when ten additional sea to lake transects were made by the author. The data obtained from these 12 transects form the major body of evidence on which the vegetation map (Fig. 1) and the following descriptions of vegetation associations are based.

The 24 species of vascular plants growing on Laysan in 1961 formed five distinct associations. These are:

1. The Nama association.

The plant which characterizes this association is Nama sandwicensis var. laysanicum, an herb which forms small rounded mounds up to 10 cm high and 40 cm in diameter. The association occurs on the beaches and seaward slopes of the island, beginning at some places within two meters of the high tide line. It reaches its best development on the north and east sides of the island, where there are large open sandy areas. Here the association extends inland for 300 to 400 meters, and is found on the crest of the island and the upper part of the inner slopes. Throughout most of the area Nama occurs alone, but in some spots scattered plants of Portulaca spp., Ipomoea pes-caprae, Boerhavia, Heliotropium, and Eragrostis can be found. In September 1961 Nama was most abundant on the north and east sides of the island where the plants were growing very thickly and were reproducing well, as indicated by the large numbers of seedlings (Fig. 2, 3). On the south and west sides of the island the individual plants tended to be more widely scattered. In July 1959, and as late as March 1961 much of the area on the north and east sides of the island was barren. Nama was present only as widely scattered individuals. The abundant development evident in September 1961 thus apparently occurred quite rapidly. This may reflect normal seasonal variation, but more likely indicated that 1961 was a year of relatively heavy rainfall. Since rainfall data are not available, this hypothesis cannot be substantiated.

It is possible that the development of a good cover of Nama can represent an early stage of vegetational succession, in which soil stabilization resulting from the presence of Nama enables seedlings of other species to become established. In places where this association comes into contact with the bunch-grass association (Fig. 5), small grass seedlings were growing among the Nama. In other places prostrate stems of the beach morning glory, some as much as 20 meters long, extended across areas covered by Nama, further stabilizing the loose sandy soil (Fig. 4). Continued observation of these areas over a period of years should provide the answer to this question.

2. The Scaevola association.

This association is characterized by Scaevola taccada, which forms a dense, highly branched shrub up to 1.5 meters in height. It typically occurs just inland of the Nama association. On the west side of the island it forms a nearly continuous strip from five to 100 meters in width. On the north, east, and south sides of the island it occurs in scattered patches, and may form "islands" within the Nama. Where the Nama association extends far inland, the Scaevola association may be present on the inner slopes. At the south end of the lake and in a few places on the west side, scattered plants of Scaevola, and occasionally a well-developed Scaevola association, appear on the lower part of the inner slopes.

The Scaevola bushes occur either singly or in groups, between which other species are often found. Toward the seaward edge of the association Nama is sometimes present. Other species in the association include Ipomoea pes-caprae, Boerhavia, Tribulus, Eragrostis, and occasionally Fimbristylis. Capparis is found in this association and occurs only as a few shrubs mixed with Scaevola on the west side of the island. At one place on the north end of the island, Sicyos hispidus was observed climbing over the Scaevola bushes.

3. The bunch-grass association.

Eragrostis variabilis, a bunch grass about one meter high, is the plant characteristic of this association, which occupies a majority of the land area on Laysan. On the west, southwest, and northwest portions of the island, the bunch-grass association occurs in a well-defined band, in places more than 500 meters wide. On the eastern part of the island the association can also be recognized although it is less well-defined and intergrades with the Boerhavia-beach morning glory-Tribulus association. The bunches of Eragrostis are spaced at intervals of one meter or more. The areas between bunches in some places contain only bare sand honeycombed with shearwater burrows, while in other places the sand is covered with Boerhavia (Fig. 6), Ipomoea pes-caprae (Fig. 7), Tribulus (Fig. 8), Nicotiana (Fig. 9), and Fimbristylis. At the north end of the island, near the inner edge of the association, vines of Sicyos spp. are found growing over the Eragrostis (Fig. 10). In some of the more open areas, Nama can be found.

Aerial photographs made in 1949 and 1961 reveal the presence of two rather distinct, more or less parallel, bands of less dense vegetation in the bunch-grass association. These bands extend throughout most of the length of the west side of the island, and alternate with three bands of denser vegetation. A survey from the ground indicates that within the less dense areas the bunches of Eragrostis are more widely spaced, and there are fewer other plants growing between the bunches. The factors responsible for this phenomenon are not yet known.

4. The Boerhavia - beach morning glory - Tribulus association.

The species which characterize this association are Boerhavia diffusa, Ipomoea pes-caprae, and Tribulus cistoides, all of which are low, creeping plants. The association occurs on the lower, inner slopes of the island, and occupies a zone from 20 to 200 meters in width, which is more or less continuous around the lake. At places within this zone each of the three characteristic species may form more or less pure stands, but they often occur intermixed. Also present in this association are widely scattered plants of Eragrostis. In the northeast part of the island the introduced shrub Pluchea indica (Fig. 11) has become established. In a few areas within the association are patches of Cynodon and Ipomoea indica. At the south end of the lake, near the inner border of this association, were found the only plants of Cyperus pennatiformis on the island.

5. The Sesuvium - Cyperus - Heliotropium association.

The association is characterized by Sesuvium portulacastrum, Cyperus laevigatus, and Heliotropium curassavicum. Sesuvium is a creeping plant with succulent leaves which forms a dense mat only a few centimeters high. Cyperus laevigatus looks superficially like a rush, grows in dense masses, and may reach a meter in height. The association occurs in a band from 10 to 100 meters in width completely around the shore of the lake. Near the lake shore Sesuvium and Cyperus laevigatus appear in pure stands; further from the shore both species occur together, mixed with Heliotropium (Fig. 12). Ipomoea pes-caprae appears frequently in this association (Fig. 13). Less commonly Tribulus and Portulaca lutea are found here. Fimbristylis occurs in two forms in this association, a larger form up to 40 centimeters high which appears identical with that which is found in the bunch-grass association, and a smaller form, about 10 centimeters high which occurs only near the lake shore.

The plants which do not participate in the formation of distinct associations are Cocos nucifera, Casuarina equisetifolia, and Messerschmidia argentea. Cocos occurs in two small groves, at the north and south ends of the lake. The Casuarina tree grows on the northwest end of the island, above the landing beach, in the transition between the Scaevola and bunch-grass associations. The single plant of Messerschmidia grows at the northwest end of the island, at the top of the beach, on the boundary between the Nama and Scaevola associations.

The only extensive barren areas on Laysan in September 1961 were an area at the south end of the island which was the site where guano was mined, the shallow bottom of the lake which becomes exposed when the

water level drops by a few inches, and an area about 50 meters north of the north end of the lake which is also apparently underwater when the level of the lake is high.

The observations presented above indicate that the vegetation has made an impressive recovery. Not only are many of the original species still present, but the structure of the vegetation appears similar to that described before the island was devastated by rabbits. The major difference evident today is the absence of three shrubs which formerly composed a significant element of the vegetation: *Chenopodium*, *Achyranthes*, and *Santalum*. Although the shrubby *Pluchea indica* could play a similar role in the formation of the vegetation, it would seem more desirable to attempt to remove the *Pluchea* and to re-establish *Chenopodium* and *Achyranthes* on Laysan, thus creating a more natural habitat.

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Photographs used for figures 2-13 were taken on Laysan Island in September 1961.

Fig. 2. The _Nama_ association at the north end of the island. In the foreground is a single clump of _Eragrostis variabilis_. The prostrate plants are _Nama sandwicensis_ var. _laysanicum_, of which individuals of several ages are present.

Fig. 3. The _Nama_ association at the north end of the island. The prostrate plants in the foreground are _Nama sandwicensis_ var. _laysanicum_, and the bunch-grass in the background is _Eragrostis variabilis_.

Fig. 4. The _Nama_ association at the north end of the island. In the foreground are vines of _Ipomoea pes-caprae_, with _Nama_ in the middle distance and background. At the left is a large clump of _Scaevola taccada_.

Fig. 5. View from north rim of island looking southeast across the central depression, showing the boundary between the _Nama_ association and the bunch-grass association. In the middle distance is a grove of coconuts planted in 1959.

Fig. 6. The bunch-grass association. The ground between the clumps of _Eragrostis variabilis_ is covered with _Boerhavia diffusa_.

Fig. 7. The bunch-grass association. The ground between clumps of _Eragrostis variabilis_ is covered with _Ipomoea pes-caprae_ and _Boerhavia diffusa_.

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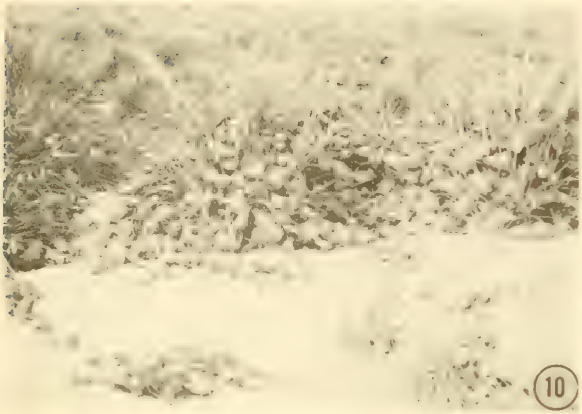
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Fig. 8. The bunch-grass association. The clumps of Eragrostis variabilis are rather widely spaced, and the ground cover is mainly Tribulus cistoides. Note the uneven ground surface, caused by the presence of many wedge-tailed shearwater burrows.

Fig. 9. The bunch-grass association. Note the Nicotiana tabacum in the center of the photograph, and Boerhavia diffusa in the right foreground.

Fig. 10. The bunch-grass association. Vines of Sicyos spp. growing among and over clumps of Eragrostis variabilis.

Fig. 11. Transition between the Boerhavia-beach morning glory-Tribulus association and the Sesuvium-Cyperus-Heliotropium association at the northeast end of the lake. In the foreground are several plants of Heliotropium curassavicum, and at the left a large shrub of Pluchea indica.

Fig. 12. The Sesuvium-Cyperus-Heliotropium association at the northeast end of the lake. The light-colored plants in the foreground are Heliotropium curassavicum, and in the background is a mat of Sesuvium portulacastrum with scattered plants of Fimbristylis cymosa.

Fig. 13. The Sesuvium-Cyperus-Heliotropium association. In the foreground are Ipomoea pes-caprae and Heliotropium curassavicum, behind which is a large stand of Cyperus laevigatus.

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Insects and other invertebrates from Laysan Island

by

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Insects and other invertebrates from Laysan Island

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Introduction

The following paper provides an annotated list of the insects and other invertebrates recorded from Laysan Island in the Leeward Chain of the Hawaiian Islands. Also the various plant species and birds are listed separately with notes on the insects that are associated with each. A bibliography lists all known sources of information on the insects of Laysan.

The fauna and flora of Laysan were subjected to a profound biological change early in this century due to the introduction of domestic rabbits. Native pritchardia palms, sandalwood trees and probably other plants characteristic of the Leeward Hawaiian Islands became extinct as the rabbits ate their own way to oblivion, creating a veritable desert island. Many native insects that were unique to Laysan went the way of their host plants, for example 7 of the 8 species of weevils and 6 of the 8 species of noctuid moths. In general, the collections of 1912 and earlier (rabbits were introduced in 1903) are of original inhabitants and those since 1923 (when the last rabbit was presumably killed) represent the survivors or new immigrants.

At the present time, there are few endemic insects on Laysan to match the unique finch and teal. The commonest example is the false chinch bug, _Nysius fullawayi fullawayi_ Usinger, a complex that is characteristic of the eastern islands of the Leeward Chain but is related, at least distantly, to lowland _Nysius_ species of the main Hawaiian Islands. Curiously, two color forms were observed among the _Nysius_, the nymphs of the widespread form being quite dark whereas those on a sedge (_Fimbristylis_) were pale. Adults of the two forms proved to be identical, even in internal genitalic characters.

Insects and other arthropods have been collected from Laysan Island by a number of scientists. Rothschild in 1894 recorded a number of moths. Schauinsland (1899) included insects in the report of his visit to the island in 1896. The bird lice collected by the Stanford Albatross Expedition in 1902 were reported by Kellogg and Paine (1910), but most of the names used were changed by Zimmerman (1948). Insects were collected by G. P. Wilder in 1905 (Perkins, 1906), by W. A. Bryan in 1911 (Dill and Bryan, 1912), by D. T. Fullaway in 1912 (1914) and again in 1923 with the Tanager Expedition. A summary of these records was given in a report of the Tanager Expedition by E. H. Bryan, Jr. (1926). The bird lice collected by the Tanager Expedition were not reported until 1940 by Thompson. This report appeared too late to be included by Zimmerman, except as a note in the final proof. Four flies

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brought back by G. P. Wilder in 1930 were recorded by Bryan (1931). Gulick (1932) included Bryan's Laysan Coleoptera and Diptera lists in a discussion of the biological peculiarities of oceanic islands. Zimmerman's Insects of Hawaii (1948 et seq.) includes many of the above records with valuable information on synonomy, keys for identification and biological data.

In 1959 the senior author spent three days in April and eight days in July on the island and reported the insects collected with a summary of all those previously recorded (Butler, 1961a). In September 1961, both authors spent six days collecting on the island and this paper is a report of this work. In June 1962 John W. Beardsley, Experiment Station of the Hawaiian Sugar Planters' Association, visited Laysan for five days. He has kindly furnished a number of new records of Lepidoptera, Coleoptera, Diptera and Hymenoptera which have been added to the manuscript of the 1961 collections and indicated by asterisks. Approximately 189 species are here recorded from Laysan with information as to the dates each species was collected and the names used in these records. In most cases absence of records for 1959, 1961, or 1962 is strong evidence that the species no longer occurs on Laysan.

Appreciation is expressed to the United States Coast Guard for providing transportation and to Dr. H. J. Coolidge for arranging for the 1961 expedition, as well as to G. P. Holland of the Canada Department of Agriculture for providing a black light trap and generator. Thanks are due to P. A. Adams, G. E. Ball, R. S. Beal, Jr., J. W. Beardsley, F. A. Bianchi, B. D. Burks, O. L. Cartwright, D. A. Chant, H. Dybas, W. J. Gertsch, L. R. Gillogly, A. B. Gurney, D. E. Hardy, D. F. Hartwick, Y. Kondo, J. P. Kramer, H. Kulzer, R. D. Pope, M. A. Miller, E. L. Mockford, C. R. W. Muesebeck, E. G. Munroe, L. M. Russell, C. H. Seevers, M. R. Smith, P. H. Timberlake, D. M. Tuttle, L. H. Weld, W. W. Writh, S. L. Wood, D. L. Wray, and C. Y. Yoshimoto for determining the specimens collected in 1961.

Systematic List of Species

A R A C H N I D A

ACARINA

Phytoseiidae

Typhlodromus (*Amblyseius*) *largoensis* (Muma), determined by D. A. Chant. 1961. On *Sicyos hispidus* Hillebrand.

Rhodacaridae

Gamasiphis sp., determined by D. M. Tuttle. 1961.

Tenuipalpidae

Brevipalpus obovatus Donnadieu (*Brevipalpus inornatus* (Banks)), det. by D. M. Tuttle. 1959, 1961. Abundant on *Scaevola* causing severe defoliation in some areas.

Argasidae

Ornithodoros capensis Neumann, det. by D. M. Tuttle. 1959, 1961. Abundant on the ground near the lake, under dead albatrosses and under *Nama*.

Ixodidae

Ixodes sp., 1959. In ear of Laysan teal.

Scheloribatidae

Scheloribates cf. *calcaratus* Jacot, det. by D. M. Tuttle. 1961. Under *Heliotropium*.

ARANEIDA

(Determined by W. J. Gertsch)

Argiopidae

Tetragnatha vicina Simon. 1959, 1961.

Lycosidae

Lycosa oahuensis Keyserling. 1959, 1961.

Salticidae

Hasarius adansoni Audouin. 1961.

Menemerus bivittatus Dufour. 1959.

Scytodidae

Scytodes striatipes Koch. 1959

Theridiidae

Coleosoma floridanum Banks. 1959, 1961. Several immature on _Pluchea_, _Sicyos_ and _Scaevola_.

Theridion rufipes Lucas. 1961.

C R U S T A C E A

ISOPODA

Porcellionides sp. (probably _P. pruinosus_) det. by M.A. Miller. 1961. (1923 and 1959 specimens not determined.)

C H I L O P O D A

Geophilidae

Honuaphilus alohanus Chamberlin. 1923.

1961 specimen not yet determined.

H E X A P O D A

THYSANURA

1959 species not identified. Abundant in duff. No specimens could be found in 1961.

COLLEMBOLA

(Determined by D. L. Wray)

Entomobryidae

Entomobrya marginata Tullberg. 1961. Under *Casuarina* in duff.

Drepanocyrtus terrestris Folsom. 1959, 1961. Very abundant in duff under *Casuarina*, under *Cynodon* and under railroad ties.

ORTHOPTERA

Blattidae

Phyllodromia sp. 1912.

Blattella germanica (L.). 1923

Cutilia soror (Brunner),(*Polyzosteria soror* Brunner). 1912.

Periplaneta americana (L.) 1912, 1959.

Pycnoscelus surinamensis (L.), det. by A. B. Gurney. 1912, 1959, 1961.

ISOPTERA

Kalotermitidae

Cryptotermes brevis (Walker). ?1923., 1959.

EMBIOPTERA

Oligotomidae

Oligotoma oceania Ross. 1923.

Oligotoma saundersii (Westwood). 1959. In duff under *Casuarina*, very abundant.

1961 species not yet determined.

DERMAPTERA

(Determined by A. B. Gurney)

Labiduridae

Anisolabis eteronoma Borelli, (*Anisolabis maritima* (Géné)). 1912, 1923, 1961.

Anisolabis perkinsi Burr. 1959. Abundant in duff and under dead albatrosses at edge of lake.

Euborellia annulipes (Lucas). 1912, 1959, 1961.

CORRODENTIA

Lepidopsocidae

Cyptophania hirsuta Banks. Det. by E. L. Mockford. 1959, 1961. Very abundant in duff under *Casuarina*.

Cerobasis sp. (undertermined nymph), det. by E. L. Mockford. 1961.

Peripsocidae

Ectopsocus fullawayi Enderlein. 1912.

Elipsocidae

Kilauella sp. 1912.

MALLOPHAGA

Menoponidae

Actornithophilus milleri (Kellogg and Kuwana). 1923.
Host: *Anous stolidus pileatus* (Scopoli), noddy tern.

Ancistrona vagelli (Fabricius), (*Ancistrona gigas* Piaget). 1902.
Host: *Pterodroma hypoleuca* (Salvin), Bonin Island petrel.

Austromenopon sternophilum (Ferris). 1923.
Host: *Anous stolidus pileatus* (Scopoli), noddy tern.

Longimenopon puffinus Thompson. 1923.
Hosts: *Puffinus pacificus chlororhynchus* Lesson - Wedge-tailed shearwater and *Puffinus nativitatis* Streets, Christmas Island shearwater.

Philopteridae

Docophoroides brevis (Dufour), (Eurymetopus taurus (Nitzsch)), 1902.
Hosts: Diomedea nigripes Audubon, black-footed albatross and Diomedea immutabilis Rothschild, Laysan albatross. "The most abundant species", according to Kellogg and Paine (1910).

Docophoroides sp. 1923.
Host: Diomedea immutabilis Rothschild, Laysan albatross.

Saemundssonia snyderi (Kellogg and Paine), (Dochophorus snyderi Kellogg and Paine). 1902, 1923.
Hosts: Sterna lunata Peale, gray-backed tern and Sterna fuscata oahuensis Bloxam, sooty tern.

Quadraceps birostris (Giebel). 1902.
Host: Sterna lunata Peale, gray-backed tern.

Quadraceps separata (Kellogg and Kuwana), 1923.
Host: Anous stolidus pileatus (Scopoli), noddy tern.

Pectinopygus gracilicornis (Piaget), (Liperus gracilicornis var. major Kellogg. 1902.
Hosts: Fregata minor palmerstoni (Gmelin), frigate bird and Sterna lunata Peale, gray-backed tern.

Pectinopygus sulae (Rudow), (Liperus potens Kellogg and Paine), 1902.
Hosts: Fregata minor palmerstoni (Gmelin), frigate bird, Sterna lunata Peale, gray-backed tern, and Sula sula rubripes Gould, red-footed booby.

Harrisoniella ferox (Giebel), (Lipeurus ferox Giebel and Lipeurus densus Kellogg). 1902.
Hosts: Diomedea nigripes Audubon, black-footed albatross and Diomedea immutabilis Rothschild, Laysan albatross.

Harrisoniella sp. (?) 1923.
Hosts: Diomedea nigripes Audubon, black-footed albatross and Diomedea immutabilis Rothschild, Laysan albatross.

Perineus concinnus Kellogg and Chapman (Lipeurus concinnus Kellogg and Chapman). 1902.
Host: Diomedea immutabilis Rothschild, Laysan albatross.

Perineus giganticulum (Kellogg), (Lipeurus confidens Kellogg). 1902.
Hosts: Diomedea nigripes Audubon, black-footed albatross, Sterna lunata Peale, gray-backed tern.

Giebelia (?) mirabilis Kellogg. 1923.
Host: Puffinus pacificus chlororhynchus Lesson, wedge-tailed shearwater.

Halipeurus mirabilis Thompson (family uncertain). 1923.
Hosts: Puffinus pacificus chlororhynchus Lesson, wedge-tailed shearwater and Diomedea nigripes Audubon, black-footed albatross.

Lunaceps sp. (family uncertain). 1923.
Host: Numenius tahitiensis (Gmelin), bristle-thighed curlew.

THYSANOPTERA

(Determined by F. A. Bianchi)

Phlaeothripidae

Haplothrips gowdeyi (Franklin). 1959, 1961. Collected from flowers of Tribulus, Cynodon, Eragrostis and Cyperus laevigatus.

Haplothrips sesuvii Priesner. 1961. Collected from flowers of Sesuvium portulacastrum, also as strays on Cynodon, Eragrostis, Pluchea and Cyperus laevigatus.

Thripidae

Frankliniella sulphurea (Schmutz). 1959, 1961. Collected from flowers of Capparis sandwichiana, Ipomoea pes-caprae, Nama, Portulaca and Tribulus.

HEMIPTERA

Cydnidae

Geotomus pygmaeus (Dallas), det. by R. L. Usinger. 1959, 1961. In duff under Cyperus and abundant at lights.

Lygaeidae

Nysius spp. 1912.

Nysius fullawayi fullawayi Usinger, det. by R. L. Usinger. 1959, 1961. Very common on Cyperus laevigatus but nymphs and adults also on Portulaca, Boerhavia, Nama and other plants. A form with pale nymphs was found only on Fimbristylis.

Reduviidae

Empicoris rubromaculatus (Blackburn). 1959.

Nabidae

Nabis blackburni White (*Reduviolus blackburni* White), det. by R. L. Usinger. 1961.

Nabis capsiformis Germar, det. by R. L. Usinger. 1912.

Anthocoridae

Orius persequens (White), (*Triphleps persequens* White). 1912.

Miridae

Cyrtopeltis modesta (Distant), det. by R. L. Usinger. 1959, 1961. On *Boerhavia* and *Nicotiana*. This is the "tobacco suck-fly", described from Central America and now a pest of tobacco and tomato in California, Hawaii, etc.

Oronomiris hawaiiensis Kirkaldy. 1896, 1912.

HOMOPTERA

Cicadellidae

Circulifer tenellus (Baker), det. by J. P. Kramer. 1961. On *Boerhavia*.

Deltocephalus sonorus Ball, det. by J. P. Kramer. 1961. On *Cynodon*.

Delphacidae

Chloriona paludum (Kirkaldy), (*Kelisia paludum* Kirkaldy, *Liburnia paludum* (Kirkaldy)). 1912.

Aphididae

Aphis medicaginis Koch. 1912?

Aphis craccivora Koch, det. by L. M. Russell. 1959, 1961. Hosts: *Tribulus*, *Boerhavia*, *Ipomoea indica*.

Aphis gossypii Glover, det. by L. M. Russell. 1959, 1961. Hosts: *Scaevola* and *Sicyos*.

Rhopalosiphum maidis (Fitch), det. by L. M. Russell. 1959, 1961. Host: *Eragrostis*.

Pseudococcidae (Determined by J. W. Beardsley)

Antonina graminis (Maskell). 1959, 1961. Hosts: *Cynodon* and *Eragrostis*.

Planococcus citri (Risso). 1959, 1961. Hosts: *Boerhavia* ?, *Capparis*, *Eragrostis*, *Ipomoea pes-caprae*, *Sicyos*, *Tribulus*, and *Cocos*.

Pseudococcus sp. (apparently new). 1959, 1961. Host: *Scaevola*.

Ferrisiana virgata (Cockerell). 1959, 1961. Hosts: *Boerhavia*, *Ipomoea indica*, *Tribulus*, *Portulaca*, *Pluchea*, *Sicyos*. Found in the crop of a Laysan finch.

Trionymus insularis Ehrhorn. 1959. Host: *Eragrostis*.

Coccidae (Determined by J. W. Beardsley)

Saissetia nigra (Nietner). 1912, 1959, 1961. Hosts: *Cyperus pennatiformis*, *Pluchea* and *Scaevola*.

Diaspididae (Determined by J. W. Beardsley)

Hemiberlesia lataniae (Signoret). 1959. Host: *Casuarina*.

NEUROPTERA

Chrysopidae

Chrysopa carnea Stephens, (*Chrysopa lanata* Banks), det. by P. A. Adams. 1959, 1961. Adults very abundant flying around *Scaevola* in 1959. Both larvae and adults very abundant on *Eragrostis* in 1961.

LEPIDOPTERA

Noctuidae

**Heliothis* sp. - *zea* group, det. by D. F. Hardwick. 1961, 1962. Hosts: Larvae believed to be this species were found on the heads of *Eragrostis* in 1961. In 1962 this species was reared from larvae feeding in flowers and green seed capsules of *Nicotiana*.

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* 1962 records provided by J. W. Beardsley.

Agrotis dislocata (Walker), det. by D. F. Hardwick. 1912, 1923, 1959, 1961. Flying at night and very abundant.

*Agrotis evanescens (Rothschild), (Peridroma evanescens Rothschild, Agrotis eremioides (Meyrick)), det. by D. F. Hardwick. 1894, 1896, 1911, 1912, 1959, 1961, 1962. Adults were reared from large cutworms found around the bases of Nicotiana in 1962.

Agrotis fasciata (Rothschild), (Peridroma fasciata Rothschild). 1894.

Agrotis laysanensis (Rothschild), (Prodenia laysanensis Rothschild). 1894.

Agrotis procellaris Meyrick, (Euxoa procellaris (Meyrick)). 1896, 1905, 1912.

Agrotis sp. larvae. Abundant under Nama, Boerhavia and Tribulus. Similar larvae were recovered from the stomach contents of a Laysan teal.

Peridroma porphyrea (Denis and Schiffermueller), (Agrotis saucia Huebner). 1905.

Pseudaletia unipuncta (Haworth), (Cirphis unipuncta (Haworth)). 1894.

*Elaphria nucicolora (Guenée). 1962. One adult at light.

Laphygma exigua (Huebner), det. by D. F. Hardwick. 1961.

Trichoplusia ni (Huebner), det. by D. F. Hardwick. 1961.

*Plusia chalcites (Esper). 1962. Adults taken flying around Scaevola at dusk.

Hypena laysanensis (Swezey), (Nesamiptis laysanensis Swezey). 1912.

Sphingidae

Herse cingulata (Fabricius). 1959, 1961.

Pyralidae

Hymenia recurvalis (Fabricius), det. by E. G. Munroe. 1896, 1905, 1912, 1959, 1961.

Hedylepta laysanensis (Swezey), (Omiodes laysanensis Swezey). 1912.

Oeobia dryadopa (Meyrick), (Pyrausta dryadopa Meyrick). 1912.

*Pyralis manihotalis Guenée. 1962. One adult at light.

Ephestia cautella (Walker), (Ephestia elutella Huebner). 1912.

Pterophoridae

Megalophipida defectalis (Walker), (Trichoptilus oxydactylus (Walker)), det. by D. F. Hardwick. 1905, 1961.
Host: Boerhavia.

Plutellidae

Plutella maculipennis Curtis. 1959. (omitted from Butler, 1961a).

Tortricidae

*Crocidosema plebiana Zeller. 1912, 1959, 1962. Several at light in 1962.

Hyponomeutidae

Pyroderces rileyi Walsingham. 1959.

Hyposomocoma notabilis Walsingham. 1912, 1959.

Tineidae

Tineola uterella Walsingham. 1923, 1959. One larval case.

Ereunetis kerri Swezey. 1912.

*Tinea despecta Meyrick (?). 1962. Numerous adults at light.

Ereunetis incerta Swezey. 1923, 1959.

Cygnodiidae

Petrochroa dimorpha Busck. 1912.

COLEOPTERA

Carabidae

Undetermined species. 1923.

Tachys oahuensis Blackburn, det. by G. E. Ball. 1959, 1961. Abundant under dead albatrosses and under drying algal surface of dry lake bed.

Staphylinidae

Undetermined species. 1923.

Carpelimus sp. (*Trogophloeus* sp.), det. by C. H. Seevers. 1959, 1961. Abundant under dead albatrosses and under drying algal surface of dry lake bed.

Coccinellidae

Scymnus debilis LeConte. 1912.

Scymnus loewii Mulsant, (*Scymnus kinbergi* (Boheman)). 1912.

Species cóllected in 1959 assoc. with *Trionymus insularis* on *Eragrostis*.

Nitidulidae

Carpophilus dimidiatus (Fabricius), det. by L. R. Gillogly. 1961.

Cucujidae

Cryptamorpha desjardinsi Guenée. 1896.

Silvanus surinamensis L. 1923. In corn meal.

Dermestidae

Dermestes ater De Geer, (*Dermestes cadaverinus* Fabricius), det. by R. S. Beal, Jr. 1896, 1911, 1912, 1923, 1959, 1961. In 1959 was found under dead albatrosses.

Attagenus plebius Sharp. 1911

Tenebrionidae

Alphitobius diaperinus Panzer. 1912

<u>Alphitobius</u> <u>piceus</u> (Oliver). 1923, 1959. In 1923 was abundant about the carcasses of dead birds. In 1959 in clump of grass.

<u>Alphitobius</u> <u>laevigatus</u> Fabricius, det. by H. Kulzer. 1961.

<u>Blapstinus</u> sp. (probably). 1959

<u>Tribolium</u> <u>ferrugineum</u> Fabricius. 1896, 1912, 1923. In 1923 in corn meal.

Cleridae

<u>Necrobia</u> <u>rufipes</u> DeGeer. 1912.

Scarabaeidae

<u>Pleurophorus</u> <u>micros</u> (Bates), (<u>Psammodius</u> <u>nanus</u> DeGeer, <u>Pleurophorus</u> <u>parvulus</u> Chevrolat), det. by O. L. Cartwright. 1923, 1959, 1961. In 1923 under dead grass. Adults abundant at sunset one evening in July 1959 and 50 were swept from the air in one minute. Erroneously listed by Butler (1961a) as <u>Bostrichidae</u>.

Cerylonidae

<u>Eidoreus</u> <u>minutus</u> Sharp, det. by R. D. Pope. 1961. Under <u>Heliotropium</u>.

Corylophidae

<u>Sericoderus</u> <u>minutus</u> Matthews, det. by R. D. Pope. 1961.

Cerambycidae

<u>Clytus</u> <u>crinicornis</u> Chevrolat. 1896.

Anthribidae

<u>Araecerus</u> <u>fasciculatus</u> (DeGeer). 1959, 1961. In 1959 associated with <u>Pluchea</u>, and erroneously listed by Butler (1961a) as Chrysomelidae. In 1961 on <u>Eragrostis</u>.

Curculionidae

<u>Dryophthorus</u> <u>distinguendus</u> Perkins. 1923.

<u>Dryotribus</u> <u>mimeticus</u> Horn. 1923.

*_Dryotribus wilderi_ Perkins. 1923, 1962. In 1962 one specimen under _Eragrostis_.

Macrancylus linearis LeConte, (_Macrancylus immigrans_ Perkins). 1912, 1923.

Oodemas laysanensis Fullaway. 1912.

Pentarthrum blackburni Sharp. 1923.

Rhyncogonus bryani Perkins. 1911.

Sitophilus oryzae (L.), (_Calandra oryzae_ L.). 1912 In food stores.

Scolytidae

Stephanoderes sp. 1912.

Hypothenemus eruditus Westwood, det. by S. L. Wood. 1961. On _Cyperus laevigatus_.

DIPTERA

Chironomidae

Undetermined species. 1923, 1959.

Telmatogeton pacificus Tokunaga, det. by W. W. Wirth. 1961. In intertidal zone on wave swept rocks.

Ceratopogonidae

*_Dasyhelia_ sp. 1962. Sweeping _Scaevola_ near beach.

Sciaridae

*Undetermined species. 1962. Near the lake.

Stratiomyidae

Brachycara latifrons James, det. by D. E. Hardy. 1912, 1959, 1961. Larvae under dead albatrosses along lake, (Butler, 1961b).

Dolichopididae

<u>Chrysosoma</u> <u>fraternum</u> Van Duzee, det. by D. E. Hardy. 1959, 1961.

<u>Hyprophorus</u> <u>praecox</u> Lehman. 1912, 1923, 1959.

<u>Hyprophorus</u> <u>pacificus</u> Van Duzee, det. by D. E. Hardy. 1961.

Phoridae

<u>Megaselia</u> <u>scalaris</u> (Loew), (<u>Aphiochaeta</u> <u>scalaris</u> Loew). 1912.

*Undetermined species. 1962.

Ephydridae

<u>Neoscatella</u> <u>sexnotata</u> (Cresson), (<u>Scatella</u> <u>hawaiiensis</u> var. <u>sex-notata</u> Torry, <u>Scatella</u> <u>sexnotata</u> Cresson). 1912, 1923, 1930, 1959, 1961. Very abundant around the lake in which the larvae live. Adults rest on the ground and on the vegetation around the lake. The adults are fed upon by the teal.

Canaceidae

<u>Canaceoides</u> <u>nudata</u> (Cresson), det. by W. W. Wirth. 1961.

Borboridae

<u>Limosina</u> <u>ferruginata</u> (Stenhammer). 1959.

<u>Limosina</u> <u>venalicis</u> (Osten-Sacken). 1923.

Asteiidae

<u>Bryania</u> <u>bipunctata</u> Aldrich. 1959.

Drosophilidae

*<u>Scaptomyza</u> sp. 1962. Near the lake.

Milichiidae

<u>Milichiella</u> <u>lacteipennis</u> Loew. 1959.

Chloropidae

<u>Siphunculina</u> <u>signata</u> Wollaston. 1959.

Tachinidae

*<u>Paradionaea atra</u> (Townsend), (<u>Leucostoma atra</u> Townsend), det. by D. E. Hardy. 1959 (not included in Butler, 1961a), 1962. A parasite of <u>Nabis</u>.

Sarcophagidae

<u>Goniphyto bryani</u> Souza Lopez, det. by D. E. Hardy. 1959, 1961.

Calliphoridae

<u>Lucilia graphita</u> Shannon. 1912, 1923, 1930, 1959.

<u>Lucilia</u> sp. ? 1912.

<u>Rhinia testacea</u> Robineau Desvoidy. 1959.

Muscidae

<u>Lispe</u> sp. ? 1912.

<u>Musca domestica</u> L. 1912, 1959.

<u>Musca vicina</u> Macquart. 1912, 1923, 1959.

Hippoboscidae

<u>Olfersia aenescens</u> Thompson (Bequaert, 1941).

<u>Olfersia spinifera</u> Leach. 1959.

HYMENOPTERA

Braconidae

<u>Chelonus blackburni</u> Cameron, det. by C. F. W. Muesebeck. 1912, 1959, 1961.

<u>Apanteles marginiventris</u> Cresson, det. by C. F. W. Muesebeck. 1959, 1961. In 1959 specimens were reared from <u>Agrotis</u>. Cocoons were found on the leaves of <u>Tribulus</u>.

Mymaridae

Unidentified species. 1912.

*<u>Polynema</u> sp. <u>reduvioli</u> Perkins or near, det. by J. W. Beardsley. 1962. Several on <u>Fimbristylis</u> near lake.

Eulophidae

Near <u>Euderus metallicus</u> (Ashmead). 1959.

Encyrtidae

<u>Xanthoencyrtus laysanensis</u> Timberlake. 1912

<u>Ectroma</u> sp. (wingless ectromic encyrtid). 1912.

Eupelmidae

<u>Bruchocida</u> sp., det. by B. D. Burks. 1961.

<u>Eupelmus</u> sp. 1905.

Pteromalidae

1959 specimen not determined.

*<u>Spalangia</u> sp., det. by P. H. Timberlake. 1961, 1962. Under dead albatrosses near lake, parasitic on flies.

Cynipidae

<u>Pseudeucoila hydrophila</u> (Perkins), det. by C. M. Yoshimoto. 1961. Associated with flies on rocks in the inter-tidal zone.

Diapriidae

*Two species collected by J. W. Beardsley, 1962, who indicates that these may be "new records or possibly the same as the doubtful identifications reported by Bryan (1926) as <u>Phaenopria</u> sp. and <u>Tropidopria</u> sp."

Scelionidae

*<u>Phanurus</u> sp. nr. <u>vulcanus</u> (Perkins), det. J. W. Beardsley. 1961, 1962. On <u>Cyperus</u> near lagoon associated with <u>Nysius</u>.

Formicidae

<u>Camponotus variegatus hawaiiensis</u> Forel, det. by M. R. Smith. 1961. Collected on board ship 36 miles west of Laysan.

<u>Cardiocondyla nuda minutior</u> Forel. 1959. Colony in stake in ground.

Monomorium destructor (Jerdon). 1923.

Monomorium floricola (Jerdon), det. by M. R. Smith and R. W. Taylor. 1959, 1961. In 1959 under dead albatross. In 1961 under driftwood log, on _Ipomoea pes-caprae_, on _Sicyos_ with _Ferrisiana virgata_.

Monomorium gracillimum (Smith). 1912.

Monomorium minimum Buckley, 1912.

Pheidole megacephala Fabricius. 1959.

Plagiolepis alluaudi Emery, det. by M. R. Smith and R. W. Taylor. 1959 and 1961. In 1959 associated with _Saissetia nigra_ on _Cyperus pennatiformis_, also on _Ipomoea pes-caprae_. In 1961 was on _Pluchea_, _Eragrostis_ with mealybugs and under a dead bird on the outer beach.

Ponera gleadowi Forel, det. by R. W. Taylor. 1961. Under railroad ties.

Ponera kalakauae Forel. 1923.

Ponera punctatissima schauinslandi Emery. (Swezey, Bish. Mus. Bul. 172:176.)

Tapinoma melanocephalum (Fabricius). 1912.

Tetramorium guineense (Fabricius), det. by M. R. Smith and R. W. Taylor. 1905, 1923, 1959, 1961. In 1959 associated with _Planococcus citri_ on _Sicyos_ and _Pseudococcus_ sp. on _Scaevola_. In 1961 under _Heliotropium_, under railroad tie and on _Pluchea_.

Ectoparasites of birds

The parasites of the birds of Laysan Island include ticks (Acarina), louse-flies or hippoboscids (Diptera: Hippoboscidae) and bird lice (Mallophaga).

The most abundant tick was the soft tick, *Ornithodoros capensis* Neumann, which was common on the ground near the lake by dead albatrosses and beneath clumps of *Nama* on the beaches. This tick probably seeks albatrosses on which to feed. Three specimens of an immature *Ixodes* sp., a hard tick, were found in the ear of a Laysan teal in 1959. No evidence of tick infestations was observed on the birds examined in 1961.

Two species of louse-flies, family Hippoboscidae, have been collected from birds on Laysan. These can be distinguished by the key given by Bequaert (1957:426) where the host relations are also discussed. *Olfersia aenescens* Thompson has the widest host range with records on various oceanic fish-eating birds such as albatrosses (*Diomedea*), boobies (*Sula*), noddy terns (*Anous*), sooty terns (*Sterna*), tropic-birds (*Phaethon*), petrels (*Pterodroma*) and shearwaters (*Puffinus*). These sea birds are all so-called "swimmers" and have similar habits of feeding at sea and nesting or roosting in populous colonies on oceanic islands.

Olfersia spinifera (Leach) is a specific parasite on the frigate birds (*Fregata*) which are its only regular breeding hosts. *Olfersia fossulata* Macquart was listed by Butler (1961a) but this record has since been found to be in error.

Bird lice of the order Mallophaga were collected by Snyder and Fisher on the Stanford Albatross Expedition of 1902 (Kellogg and Paine, 1910) and by the 1923 Tanager Expedition (Thompson, 1948). The following list was prepared from these reports and Zimmerman's (1948) discussion.

Host List of Mallophaga from Laysan Island

Diomedea nigripes Audubon   Black-footed Albatross
- *Docophoroides brevis* (Dufour)
- *Halipeurus mirabilis* Thompson
- *Harrisoniella ferox* (Giebel)
- *Harrisoniella* sp.
- *Perineus giganticulum* (Kellogg)

Diomedea immutabilis Rothschild   Laysan Albatross
- *Docophoroides brevis* (Dufour)
- *Docophoroides* sp.
- *Harrisoniella ferox* (Giebel)
- *Harrisoniella* sp.
- *Perineus concinnus* (Kellogg and Chapman)

Puffinus pacificus chlororhynchus Lesson   Wedge-tailed Shearwater
- *Giebelia (?) mirabilis* Kellogg
- *Halipeurus mirabilis* Thompson
- *Longimenopon puffinus* Thompson

Puffinus nativitatis Streets   Christmas Island Shearwater
    Longimenopon puffinus Thompson

Pterodroma hypoleuca (Salvin)   Bonin Island Petrel
    Ancistrona vagelli (Fabricius)

Sula sula rubipes Gould   Red-footed Booby
    Pectinopygus sulae (Rudow)

Fregata minor palmerstoni (Gmelin)   Frigate Bird
    Pectinopygus gracilicornis (Piaget)
    Pectinopygus sulae (Rudow)

Numenius tahitiensis (Gmelin)   Bristle-thighed Curlew
    Lunaceps sp.

Sterna lunata Peale   Gray-backed Tern
    Pectinopygus gracilicornis (Piaget)
    Pectinopygus sulae (Rudow)
    Perineus giganticulum (Kellogg)
    Quadraceps birostris (Giebel)
    Saemundssonia snyderi (Kellogg and Paine)

Sterna fuscata oahuensis Bloxam   Sooty Tern
    Saemundssonia snyderi (Kellogg and Paine) Host record from Marquesas.

Anous stolidus pileatus (Scopoli)   Noddy Tern
    Actornithophilus milleri (Kellogg and Kuwana)
    Austromenopon sternophilum (Ferris)
    Quadraceps separata (Kellogg and Kuwana)

Insects as food for birds

There are only two insectivorous birds now living on Laysan, the Laysan finch and the Laysan teal. Unfortunately only a few stomach contents of each were available for study. In July, 1961, the stomach of one finch was found to be packed with the mealybug, Ferrisiana virgata (Cockerell). This mealybug was very common on the stems of Boerhavia, Ipomoea indica, Tribulus, Portulaca, Pluchea and Sicyos. The birds were observed to be very active around some of these plants, picking at the stems and buds and were undoubtedly picking off mealybugs.

Laysan teal were observed feeding on cutworms and flies. Cutworms were obtained from teal stomach contents collected in August, 1959 and September, 1961. These Agrotis larvae were very abundant beneath Nama, Boerhavia and Tribulus. It was in areas with these plants that teal were observed feeding at night. The larvae have not been identified but the most abundant species of moth collected at night was Agrotis dislocata (Walker), which was probably the species being fed upon by the teal.

In April 1959, several teal were observed feeding on the fly, Neoscatella sexnotata (Cresson), by the lake. Several teal ran together down-wind across the edge of the lake stirring up the flies. Then they wheeled in a semi-circle up into the wind, "herding" the flies into the wind and snapping them up. The larvae of these flies were very abundant in the highly saline waters of the lake. The populations of this fly may be more stable than those of the cutworms, which depend upon plants and which are attacked by a number of insect parasites. The muscoid flies which were very abundant around the camp in July 1959 and September 1961 were also fed upon by the teal.

J. W. Beardsley (personal communication) reported that in June 1962, "I pulled back the edge of a tent to collect some of the many adults of Agrotis evanescens which had taken refuge there. As the moths scattered, two teal appeared suddenly on the scene and snapped up the moths as fast as they could."

It is interesting to speculate that perhaps one of the factors influencing the extinction of two of the endemic birds, the Laysan honeyeater and the miller bird, was the apparent disappearance of several species of endemic noctuids upon which they may have fed. Agrotis laysanensis (Rothschild), Agrotis procellaris Meyrick and Hypena laysanensis (Swezey) are three endemic species which have not been collected since 1912. Three other species of noctuid moths have not been collected since that date either: Agrotis fasciata Rothschild, Peridroma porphyrea (Denis and Schiffermueller) and Pseudaletia unipuncta (Haworth). Two moth species were apparently able to survive, one an endemic Laysan species, Agrotis evanescens (Rothschild) and the other, Agrotis dislocata (Walker), endemic in the Hawaiian Islands. It is upon these two species that the Laysan teal feeds. Two additional species of noctuids are probably of recent introduction, Heliothis sp. near zea group and Trichoplusia ni (Huebner). The Heliothis was feeding on the heads of Eragrostis and on the flowers and seed pods of Nicotiana, so would be out of reach of the teal. The finches were observed feeding upon the grass heads, however.

The insects associated with plants

Boerhavia diffusa Linnaeus

Aphids, Aphis craccivora Koch, were abundant on the leaves and stem tips. Mealybugs, Ferrisiana virgata (Cockerell) were collected on the stems, particularly in close contact with the sand. Large cutworm larvae, Agrotis, were abundant in the sand beneath the plants. Fifty were dug up in one square yard. A moth, Megalorhipida defectalis (Walker). was abundant around the plants. A spiny larva, believed to be of this species, was collected on the plants where it was feeding on the leaves. A green mirid, Cyrtopeltis modesta (Distant) was found on the plants in some numbers.

Capparis sandwichiana De Candolle

Thrips, Frankliniella sulphurea (Schmutz), were present in the flowers. Ants were quite numerous on the stems but only one mealybug specimen, Planococcus citri (Risso), was found in the center of a leaf. Chrysopid eggs were observed. A caterpillar (undetermined) was found feeding on the leaves causing skeletonized spots and ragged edges.

Casuarina equisetifolia Linnaeus

A few armored scales, Hemiberlesia lataniae (Signoret), were found on the branches. In the duff beneath the tree there were embiids (Oligotoma saundersii (Westwood)), Collembola (Entomobrya marginata Tullberg and Drepanocyrtus terrestris Folsom), psocids (Cryptophania hirsuta Banks) earwigs (Anisolabis perkinsi Burr.), sowbugs (Porcellionides sp.) and lepidopterous larvae (undetermined) in silken tubes.

Cocos nucifera Linnaeus

Mealybugs, Planococcus citri (Risso), were found on the palms at the north end of the lake.

Cynodon dactylon (Linnaeus) Persoon

Thrips, Haplothrips gowdeyi (Franklin), were collected from the plants. Mealybugs, Antonia graminis Maskell, were abundant on the stems at the lower nodes. Collembola, Drepanocyrtus terrestris Folsom, were abundant beneath the plants. Leafhoppers, Deltocephalus sonorus Ball, were present, as well as Nysius fullawayi fullawayi Usinger.

Cyperus laevigatus Linnaeus

Adults of Nysius fullawayi fullawayi Usinger were abundant.

Cyperus pennatiformis var. bryanii Kükenthal

Black armored scales, Saisettia nigra (Nietner), were extremely abundant, mostly on the under sides of the leaves but also on the flower heads. The scales were attended by ants, Plagiolepis alluaudi Emery. Only a few mealybugs (undetermined) were present.

Eragrostis variabilis (Gaudichaud) Steudel

Much of the grass in September 1961 showed the effects of injury by mealybugs and aphids. The older leaves were black with fungus-covered honeydew. Three species of mealybugs were present: Antonina graminis (Maskell) in colonies on the upper roots and on the lower

stems, Planococcus citri (Risso) and Trionymus insularis Ehrhorn on the leaves. Honeydew was present and the mealybugs were attended by ants which nested at the crowns of the plants. Two species of ants were collected: Pheidole megacephala F. and Plagiolepis alluaudi Emery. According to the 1959 records, coccinellids were also associated with the mealybugs but specimens are not now available. None were collected in 1961.

Aphids, Rhopalosiphum maidis (Fitch), were abundant on the leaves. Ants were associated with them also. Lacewing larvae and adults, Chrysopa carnea Steph., were abundant on and around the plants. In September 1961, 58 adults were swept from one clump of grass. A noctuid larva, believed to be Heliothis sp. zea group, was present on the heads. Thirty larvae were collected in 1000 net sweeps. Another caterpillar, (undetermined but possibly Hymenia recurvalis (Fabricius)), was very abundant on the lower portions of the stems.

A thrips, Haplothrips gowdeyi (Franklin) was abundant on the grass heads. A few beetles, Araecerus fasciculatus (DeGeer), were collected on the grass heads but they may not be closely associated with the plants.

Fimbristylis cymosa R. Brown

Nysius fullawayi fullawayi Usinger with pale nymphs were found only on this plant.

Heliotropium curassavicum Linnaeus

A small green looper larva, possibly Trichoplusia ni (Huebner), was feeding on the leaves. Underneath the plants were ants (Tetramorium guineense (Fabricius)), sowbugs (Porcellionides sp.), earwigs, roaches (Pycnoscelus surinamensis (L.)), and mites (Scheloribates cf. calcaratus Jacot).

Ipomoea indica (Burmann) Merrill

Aphids, Aphis craccivora Koch, were abundant on the stem tips. Mealybugs, Ferrisiana virgata (Cockerell) were collected. Larvae of the sweet potato hornworm, Herse cingulata (Fabricius), might be present on this plant but none were observed.

Ipomoea pes-caprae (Linnaeus) Sweet

Mealybugs, Planococcus citri (Risso), were collected on the stems where they were often attended by ants. Two species were collected: Monomorium floricola (Jerdon) and Plagiolepis alluaudi Emery. Thrips, Frankliniella sulphurea (Schmutz), were present in the flowers. Larvae of the sweet potato hornworm, Herse cingulata (Fabricius), might be present on this plant but none were observed. A brilliant metallic-green dolichopodid fly was abundant, resting on the leaves.

Nama sandwicensis A. Gray var. laysanicum A. Brand

Some small plant bugs, Nysius fullawayi fullawayi Usinger, were present on the plants on the beaches of the east shore. Pyralid larvae, undetermined, were found in webbing at the crown of the plants and in the sand. Beneath the plants Agrotis larvae of apparently two species,

one a large dark-grey color and the other a smaller and green, were very abundant in the sand. A thrips, Haplothrips sesuvii Priesner, was in the flowers.

Nicotiana tabacum Linnaeus

A mirid, Cyrtopeltis modesta (Distant) was quite abundant, both the nymphs and adults. A very large cutworm was observed feeding on the leaves at night in 1959 and 1961 and caused extensive leaf injury. Beardsley in 1962 reared Agrotis evanescens (Rothschild) from the base of injured plants and reared Heliothis sp. near zea from flowers and green seed pods.

Pluchea indica (Linnaeus) Lessing

An armored scale, Saissetia nigra (Nietner), was very abundant on the undersides of the leaves. A mealybug, Ferrisiana virgata (Cockerell), was also present. The ant, Tetramorium guineense (Fabricius), was collected on this plant. A few beetles, Araecerus fasciculatus (DeGeer), were collected.

Portulaca lutea Solander

A mealybug, Ferrisiana virgata (Cockerell), was present and a few Chelonus blackburni Cameron were swept from the plants.

Scaevola sericea Vahl

Aphids, Aphis gossypii Glover, were present on the undersides of the leaves. Also on the undersides of the leaves were scales, Saissetia nigra (Nietner), as well as on the stems. Mealybugs, Pseudococcus sp. apparently new, were found at the inside axil of the large leaves where they were protected in the hairy material. Some were also up on the leaves at the terminal buds. The ant, Tetramorium guineense (Fabricius), was attending the aphids, mealybugs and scales and a colony was found in the ground at the base of a plant. Golden-eyed lacewing adults, Chrysopa carnea Steph., were abundant and were flying over the leaves. A dozen or so were observed in one small portion of a bush in July 1959.

A very heavy infestation of spider mites, Brevipalpus obovatus Donnadieu, was present at one location on the south-east coast. The lower leaves of the plants had turned rusty yellow and were dropping off. This seriously reduced the cover, shade and concealment from enemies for the ground-nesting birds beneath, particularly the red-tailed tropic birds.

Numerous small spiders, Coleosoma floridanum Banks, were hidden in light webs in curled leaves. The plants were a favorite resting place for the extremely abundant muscoid flies, and their fecal specks were very noticeable on the leaves.

Sesuvium portulacastrum Linnaeus

The leaves were chewed. Larvae were present in silken tubes extending into the ground. Small cream-white moths were abundant about the plants. A thrips, Haplothrips sesuvii Preisner, was found in the flowers.

Sicyos hispidus Hillebrand

Two species of mealybugs, Planococcus citri (Risso) and Ferrisiana virgata (Cockerell), were present and attended by two species of ants, Tetramorium guineense (Fabricius) and Monomorium floricola (Jerdon), respectively. The aphid, Aphis gossypii Glover, was also collected.

Tribulus cistoides Linnaeus

Dark green aphids, Aphis craccivora Koch, were feeding on the leaves and the petioles of the flowers.

Scattered individual mealybugs, Ferrisiana virgata (Cockerell) and Planococcus citri (Risso) were found on the stems, leaves and seeds. No ants appeared to be attending them. The thrips, Haplothrips gowdei (Franklin) and Frankliniella sulphurea (Schmutz), were present in the flowers.

Small yellow to bright green larvae (undetermined) with black heads were found feeding on the leaves and flowers, often hidden in the bracts. Sometimes there were two in a single bloom. They fed when the young leaflets were still closed together and made "windows" in the leaflets.

Cutworms, Agrotis sp., were abundant in the sand beneath the plants. In one 3 square foot area 25 larvae were dug up. Cocoons of Apanteles marginiventris Cresson were found on the leaves. A few adults of this species were reared from Agrotis larvae, and some adults were swept from the plants.

Insects and other animals associated with the lake

One of the outstanding topographical characteristics of Laysan is the central lake with its highly saline water. There are several animals that are associated with the lake and the surrounding area.

In the *Sesuvium-Cyperus-Heliotropium* plant association immediately surrounding the lake there was an amphipod (undetermined) which was very abundant in the damp ground around the roots. There were also ants (*Tetramorium guineense* (Fabricius)), sowbugs (*Procellionides* sp.), earwigs (*Anisolabis perkinsi* Burr), roaches (*Pycnoscelus surinamensis* (L.)), and mites (*Scheloribates* cf. *calcaratus* Jacot). An earthworm was also present and, according to Schauinsland (1899:90), was named *Pontodrilus ephippiger* Rosa var. *laysanianus*.

Beneath the salt and algal crust in the damp unvegetated area surrounding the lake, one could find the above mentioned amphipod and earthworm, particularly under the carcasses of dead albatrosses. There were also two common beetles, a carabid, *Tachys oahuensis* Blackburn, and a staphylinid, *Carpelimus* sp. These were found together beneath pieces of the rubbery dried algae.

The most abundant animals in the lake were brine shrimp and a fly larva. These animals live in a very rigorous habitat as, in addition to the high salt content of the water, it was also quite hot. Temperatures were taken at 3 pm on July 25, 1959, and were as follows:

Distance from shore in yards	Depth of water in inches	Water temperature C°
5	1½	39.3
11	3½	38.5
13	5	34.0 at surface 32.0 in mud
16	19	33.0

There was a distinct thermocline to a cooler temperature at approximately the 5 foot depth which was noticed when swimming in the lake.

Brine shrimp, *Artemia*, were extremely abundant and were continuously swimming against the currents. In some shallow areas they were so dense that the water appeared to be red. In addition to the *Artemia*, Schauinsland observed the larvae of a little dipteron, *Neoscatella sexnotata* (Cresson). These larvae stand perpendicular to the surface of the piece of alga or stone to which they are attached with two caudal hooks. They appear to maintain a large air bubble at the entrance to the tube-like body. These larvae were observed living in the water from the edge of the lake to depths of 6 to 7 feet. The pupae were much

darker in color and probably come to the surface to permit the adult to escape. There were large "windrows" of dark exuviae along the margin of the lake and along the margins of previous water levels. The adult flies were extremely abundant, resting on the damp areas surrounding the lake and on the vegetation. They were very noticeable on the stems of *Cyperus* where they lined up on the shady side of the stems. There were also large numbers resting on the other plants around the lake, from which the flies flew up in small black clouds when disturbed. It was upon these flies that the Laysan teal were observed feeding in April 1959.

Insects and the windward lagoon

On the wet surfaces of the rocks in the intertidal zone along the windward lagoon, two species of flies were collected in 1961. Dr. Hugh Caspers conducted some studies in this area in April 1959 but the report of his observations is not available. The most common fly in 1961 was the chironomid, *Telmatogeton pacificus* Tokunaga. The other fly was a canaceid, *Canaceoides nudata* (Cresson). A cynipid, *Pseudeucoila hydrophila* (Perkins), was associated with these flies.

Land snails

The current list of land snails from Laysan consists of *Lamellidea gracilis* (Pease) and *Tornatellides bryani* Pilsbry and Cooke, according to Y. Kondo.

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Notes on the Wedge-tailed Shearwater at Heron Island, Great Barrier Reef, Australia

by

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Notes on the Wedge-tailed Shearwater at
Heron Island, Great Barrier Reef, Australia

by

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Introduction

During three weeks of the southern summer, December 10, 1960 to January 1, 1961, two of us (Gross and Moulton) had an opportunity to study the behavior and early nesting activities of the Wedge-tailed Shearwater Puffinus pacificus chlororhynchus Lesson, locally known as the Mutton Bird, on Heron Island in the Capricorn Group at the southern end of the Great Barrier Reef. Facilities of the Heron Island Research Station of the Great Barrier Reef Committee are gratefully acknowledged.

Moulton was conducting a research program on Heron Island at the Marine Research Station during October and November, 1960, during which he observed the annual arrival of the birds, their mating and nesting, and recorded their calls. Thus the period of observation extended through three months of the bird's breeding season of 1960-1961, and in December Gross and Moulton worked together. The topography and vegetation of Heron Island have been described by Fosberg, Thorne, and Moulton (1961).

The Wedge-tailed Shearwater is one of the most common and widespread shearwaters of the tropical and semi-tropical parts of the Pacific. Its breeding range extends from the Revilla Gigedo Islands off Baja California to the Seychelles and Mascarene Islands off Madagascar and from the Pescadores Islands in Formosa Straits to Henderson Island in the southeastern Tuamotus. Its southernmost breeding stations are off the southeast coast of Australia and its northernmost in the Leeward Hawaiian and Bonin Archipelagoes. Its distribution and systematics have been discussed by Murphy (1951) who recognized two subspecies, Puffinus pacificus pacificus of the Kermadecs, Fijis, and Norfolk Island, and P. p. chlororhynchus, occupying the rest of the range. Oliver (1955) believes that these birds do not migrate, but remain in the seas adjacent to the breeding islands outside the nesting season; their great powers of

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flight allow them to range widely, however, as indicated by Murphy's report of specimens taken hundreds of miles from any possible breeding station.

The Wedge-tailed Shearwater is known by several common names in different areas of its distribution, such as Wedge-tailed Puffin, Wedge-tailed Petrel, Mourning Bird, Moaning Bird, or Ghost Bird because of its call, Black Burrowers and the usual name, Mutton Bird. The latter name is applied to several other species such as *P. tenuirostris*, *P. griseus*, *P. carneipes*, and *P. bulleri*. The name Mutton Bird arose from the taste of the flesh.

Description

The plumage of the Wedge-tailed Shearwater shows two color phases. The dark phase has the upper surface of the plumage a sooty brown, the primaries and tail are black, the chin, throat, and forehead brownish gray, and the remainder of the under surface a dusky brown. In the light phase the birds are brown above, but the under parts are white with gray along the borders between the two colors. The under tail coverts are black in both forms. The bill is slate or lead color, the iris dark brown, the tarsus, foot, and nails flesh color, and the outer edge of the outer toes darkly pigmented. The outer toes are stronger, thickened, and calloused, probably due to the greater use of these toes in digging.

Only the dark forms are found on Heron Island. The Wedge-tailed Shearwater is polymorphic, the light and dark phases occurring together in some colonies, while a third intermediate form is sometimes found (Murphy, 1951). Although the proportion of light phase birds is higher in the northern part of the range, these color phases do not constitute geographical subspecies, as was formerly maintained (Loomis, 1923). Geographical variation, both in size and in color phase proportions, occurs within the subspecies *Puffinus pacificus chlororhynchus*. A number of albinistic and semi-albinistic forms of the Wedge-tailed Shearwater have also been reported (Munro, 1944).

Measurements in millimeters and weights in grams of five specimens of Wedge-tailed Shearwaters from Heron Island are given in Table I. The measurements and weights are of living birds, sexes not determined. The nostril-bill measurements were from the anterior edge of the nostril opening to the tip of the bill. The eye-bill measurement was the distance from the anterior edge of the eye to the tip of the bill. (The other measurements are standard.)

Table I

Measurements in millimeters and weights in grams of five adult Heron Island Wedge-tailed Shearwaters

	1	2	3	4	5	Mean
Length	423	436	438	441	449	437
Extent	995	1025	1000	1016	1036	1014
Wing	294	295	298	292	289	294
Tarsus	51	52	50	43	48	49
Foot	50	53	55	53	58	54
Bill(culmen)	30	36	30	38	33	33
Nostril-bill	30	36	29	33	33	32
Eye-bill	50	55	50	55	53	53
Weight	396	410	407	—	—	404

Some measurements of 5 birds, 2 males and 3 females, from the Tonga Islands were made by Davidson (1931) on January 6, 1921:

	Wing	Tail	Culmen	Tarsus
Average 2 males	289.0	135.5	41.25	46
Average 3 females	289.0	135.0	39.0	39.0

Arrival at Heron Island

No Wedge-tailed Shearwaters were observed on Heron Island when Moulton arrived on the island for the first time on October 4, 1960. He captured and photographed one of the first arrivals of 1960 near the Marine Station on October 8, 1960, and the first call notes of the year were heard later that night. By October 11 large numbers had arrived and were present from then on until our departure. Many of the shearwaters fed at sea during the day, often with Noddy Terns, Anous sp. None of them were seen on the island during the day, except in burrows, but thousands of them poured onto the island at dusk and departed the next morning. By November many fresh burrows had been excavated in the sand and apparently old ones were renovated and lengthened.

The Nest Burrow

The openings of the tunnels leading to the nesting cavity are usually wider than high and large enough to admit the birds with room to spare. Five representative openings were 10 x 15, 9 x 15, 13 x 13, 10 x 18, and 20 x 25 centimeters in size. The length of tunnel varies with repeated use, the character of the soil, and obstructions encountered in digging. In some cases in which the tunnel was less than half a meter long we could see the egg or the incubating bird; a few tunnels were as long as 3 meters. The majority of the nests could be easily reached by inserting the arm and required no excavation to obtain the adult bird or its egg. The nests had only a scant lining of grasses and twigs and it was not unusual to find the egg on the sandy bottom of the nesting bowl without any nesting material. The excavated tunnels started down usually at a slight angle and then paralleled the surface of the ground. The burrows of former years were renovated and were dug much longer than the freshly dug tunnels.

Several of the birds were seen digging their nesting holes at the start, in which the legs and feet play an important role. The bird would rest on its side and by extremely rapid strokes of the leg would make the sand spray upwards for as much as a meter. Presently the bird would turn to its other side and continue digging with the opposite foot. The tarsi of the Wedge-tailed Shearwater are long and strong and well adapted to digging. The beak, contrary to what one might expect, was not used to any great extent in digging. The burrows on Heron Island were very close together, sometimes 3 or 4 to the square meter, so that the ground was almost completely undermined. In walking across a nesting area, one was constantly breaking through into the burrows even in places where the surface of the ground seemed to be firm and solid. Many of the nesting burrows on Heron Island were under and among the tangled roots of Pisonia and other trees. In a section of the nesting area near the guest houses of the hotel the birds tunneled under the buildings and other structures. A large water tank resting on the ground was so completely undermined with tunnels made by the birds that it sank deeply on one side and had to be reset. The custom is to lay chicken wire (wire netting) around buildings to prevent burrowing underneath.

The cabin which the senior author occupied was in the midst of a heavily populated section of the shearwater colony. An area of 20 x 25 meters had been cleared of vegetation and leveled directly in front of our cabin. Approximately 50 pairs of birds continued to use the area in spite of the radical changes made by man's intrusion. Banding of birds elsewhere has revealed that other shearwaters and petrels persist in occupying the traditional grounds, even returning to the same burrow if it remains intact from one nesting season to the next.

The Egg

The onset of egg-laying occurred with surprising uniformity. Although more than twenty burrows in different sections of the island

were examined almost daily, the first eggs were not found until 15 December. On that date we suddenly found eggs commonly, the majority of nests examined contained an egg where before there had been none, and several eggs were found freshly laid on the surface of the ground.

The occurrence of a large number of eggs on the open ground is difficult to explain, but it is possible deposition on the ground occurred when a burrow had not yet been excavated or when a burrow had been filled in.

A nesting area near the hotel buildings was very much dug up by the birds. The area was smoothed over by a tractor scraper, filling up all of the nesting tunnels. It was at the beginning of the egg-laying season, and as a result the birds seemed bewildered when they appeared in the evening. Many eggs were deposited on the ground during the night, but such eggs were never incubated, although according to Howell and Bartholomew (1961) on Midway Island "the Wedge-tailed Shearwater commonly nest in shallow depressions of the sand. The nest is usually in at least partial shade, but in rare instances nests were placed completely in the open." In 1910 on Raoul Island of the Kermadec group many eggs of the Wedge-tailed Shearwater were laid on the surface of the ground; in the previous year a storm filled many of the burrows with sand and rocks, which set so hard the birds could not burrow (Oliver, 1955).

The single egg of the Wedge-tailed Shearwater is elongate, ovate in shape and pure white in color with a matte surface. Ten eggs measured by us varied in length from 60.3 to 68.2 mm. (mean 62.7), in width from 40.7 to 43.0 mm. (mean 41.8), and in weight from 53.7 to 64.1 grams (mean 59.0). These means are close to those given by Bent (1922). Other data have been published by Oliver (1955) and Willett (1919) for other islands.

When boiled, the egg was fully as palatable as a hen's egg and did not have the fishy odor or taste that are associated with the eggs of many other sea birds. The yolk was a pale yellow. The white of the Mutton Bird's egg is like that of the hen's egg. It is not surprising that the Maoris of New Zealand prize the eggs as well as the flesh of other shearwaters as food.

Sex Determination

Since theshearwaters exhibit no external sexual dimorphism we used the method used by Serventy (1956a) in sexing petrels and shearwaters by an examination of the cloaca. This method is applicable during the period of sexual activity. The difference between the sexes lies in the great dilation of the cloaca associated with the swelling of the oviduct of the female, to allow for the passage of the large egg. We examined a series of birds and found the method easy and apparently accurate. To check the sexing, an incubating bird determined to be a male by the cloacal examination was collected; dissection proved the diagnosis to be correct. We examined six birds

from nests soon after the egg was deposited; all six were males. This was evidence that the male takes part in incubation and probably initiates it. Three males were banded which were incubating eggs, and in one case a female replaced the male after six days. Unfortunately, the other two nests were accidentally destroyed. It is certain that both male and female normally take part in incubation. The male may be the one of the pair to excavate the burrow, but no sex determination was made of the few birds seen digging burrows. More observations are needed to determine the time spent on the nest by each sex and the number of times changes are made during the entire period of incubation.

Behavior

The door and a window of our cabin faced the cleared area, giving us an unexcelled opportunity to observe, by means of flashlights and electric lights, the activities of the birds at all hours of the night. Here we could repeatedly record the time of their arrival and departure and note the details of their behavior.

During the day the shearwaters were not in evidence on the island; all but those incubating in their burrows were scattered, feeding out at sea. Some were seen by various observers more than a hundred miles from the colony. They seem to be widely dispersed in small groups but have been seen concentrated in very large numbers, sometimes with Noddy Terns, in places where food was abundant. The Wedge-tailed Shearwaters do not feed on fish to any great extent. The food, judging from stomach examinations, is chiefly cephalopods such as squids, shrimps, and other small crustaceans which are caught near the surface of the water. Far out at sea single individuals or small groups of 2 to 5 may be seen seeking food and occasionally sitting on the water. The shearwaters are expert fliers and with their long narrow wings maneuver expertly as they skim closely over the waves with little movement of their wings; their flight resembles that of the albatrosses, but with more flapping.

On a typical evening in December the Noddy Terns were the first to return; a few of them would be seen going to or from the island at any hour of the day, but by 6:30 p.m. the vanguard of the great masses of terns coming to the Heron Island rookery for the night had arrived. Some of the birds came in as single individuals, but most of them were in groups of ten or more. By 7:00 p.m. the terns were arriving by the thousands all along the eastern side of the island — as many as 350 per minute within 30 meters of the beach.

At 7:45 p.m. the light was growing dim and suddenly there was an awe-inspiring roar of wings: the shearwaters had arrived off shore. Thousands of them were circling and flying about before venturing inland. A few minutes later they would fly over like a swarm of huge bats. They continued to fly back and forth over the entire nesting area of the island.

At the clearing near the camp a few minutes after 8:00 p.m. a dozen or more shearwaters circled high above the tree tops. It was too dark to see the details of the nesting area without lights, but the birds were darkly silhouetted against the starlit sky above. The birds uttered no calls. As they circled and came nearer and nearer to the ground they seemed to be searching for a proper place to land near their burrows. Around 8:30 p.m. the first bird would literally drop to the ground with a distinct thump in a resounding pancake landing, withdrawing the feet and folding the wings at about $1\frac{1}{2}$ meters above ground. It did not land on its feet nor did it break its downward speed by using its tail and wings effectively. (Odd birds crashed into lighted windows.) The birds were not stunned but, lingering long enough to get their bearings, they scooted towards the entrance of a burrow where they might be met by their mates. At the proper burrow the two birds seemed to exchange subdued calls of recognition. One newly-arrived bird appeared to be feeding its mate by regurgitation, but we were unable to observe the transfer of the food. The two birds came close together and one of them repeatedly ran its beak through the feathers of the neck and head of its mate. This behavior may have been a part of the courtship performance. At such times a pungent oil was emitted from the nostrils as occurs in other petrels. Soon other birds made similar landings in quick succession, and the majority of them joined their mates, not in the burrows as might be expected but on the open ground where they remained for the night. Courtship including copulation usually took place not in the burrows but on open ground. The birds do not stand upright on their feet but rest their bodies flat on the sand. A bird entering a wrong burrow was vigorously ousted by the tenant which obviously was not its mate. This ousting was accompanied by loud yowls and violent flappings of wings. At this time the calls and weird sounds of the birds made the night hideous and ghostly. They came from thousands of birds in every part of the nesting area of the whole island. The calls were not bird-like and not musical but were high-pitched cat-like squalls mingled with low-pitched murmurs. At times their calls resembled those of cows and their calves, and again it was like a lively and spirited cat serenade. The silence of day was rudely broken, as darkness descended, by their weird dolorous wails.

The chorus of thousands of shearwaters mingled with the high-pitched calls of the noddy terns in their wooded rookery was kept up throughout the night without any marked intermission. The birds were still going strong at 5:00 a.m., but soon thereafter the volume of sounds began tapering off. There was much activity among the shearwaters, the birds running rapidly and awkwardly, scooting over the ground with their wings upheld to balance themselves. Evidently with their heavy bodies and wing spread of a meter it was difficult to take off in a restricted area. Instead there would be a stampede of birds rushing along the ground to the shore along well-defined paths. Some of the birds in their confusion banged against our camp with such force that it was surprising that no dead or stunned birds were found on Heron Island. The exodus was rapid and by 5:30 a.m. no birds were seen on the breeding grounds. The thousands of shearwaters were off for another day on their hunting grounds at sea.

Calls

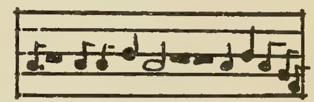
We were particularly interested in the Mutton Bird because of the extent to which its breeding and nesting behavior parallel that of Leach's Petrel, Oceanodroma leucorhoa (Vieillot), which has been studied for many years at the Bowdoin Scientific Station at Kent Island in Canada's Bay of Fundy (W.A.O. Gross, 1935; Griffin, 1940; A.O. Gross, 1947; Huntington, 1962.) Actually, although members of the same order (Procellariiformes), the two birds are in different families (Procellariidae - Shearwaters and Fulmars, and Hydrobatidae-Storm Petrels) which share many characteristics, including nesting underground on offshore islands, laying a single egg, going and coming by night, feeding at sea, calling on the breeding grounds, the sexes being alike externally, and ejecting a stomach oil of characteristic odor.

The calls of Leach's Petrel have been recorded by Huntington, Philip D. Walls, Lowry C. Stephenson, and D. Barry May. This petrel makes a "flight call" heard at night over the nesting grounds and occasionally at sea, and a "burrow call" or "purring call" produced in the burrow. The purring call may be rarely produced on the wing, and the flight call is commonly produced in the burrow. While the flight call is produced somewhat irregularly, the purring call is produced over and over again by an undisturbed bird. When it is heard from a burrow, usually two birds are present, and the call is often heard as a duet (Palmer, 1962, p. 228). The flight call consists of two distinctive staccato phrases, separated by a brief pause (Table II); it varies greatly in pitch and pattern details.

The Mutton Bird, on the other hand, produces a moan-like call which varies in pitch from one individual to another, but is too simple to allow variation in pattern. It is made by birds lying on the ground and by birds in the burrow. It may sound like a caterwauling, a howl, a low moan, and during fighting like a snarl. The birds are quiet whenever they enter a lighted area, and we never heard them calling at sea or on the wing.

Recordings were made of Heron Island Mutton Birds in the vicinity of the laboratory building of the Great Barrier Reef Committee on October 14, 1960, with a Magnecorder PT6-BN and a PT6BA2HZ tape recorder and an Electro-Voice 630 microphone around 10:00 p.m. at 3 3/4 inches/second. Recordings of Leach's Petrels were made on Kent Island, Grand Manan, on May 25, 1962, around 10:45 p.m. with a Magnemite Recorder 610-EV, and Electro-Voice 630 microphone and a 30-inch parabolic reflector at 15 inches/second; other recordings were made on Gull Island, 20 miles south of St. John's Newfoundland, at 1:45 a.m. on August 14, 1962. Sound spectrograms were prepared on a Kay Vibralyzer vibration frequency analyzer, and time-frequency data are taken from those preparations. Characteristics of Mutton Bird and Leach's Petrel calls are shown in Table II.

TABLE II

Call	Duration	Frequency Span	General description
Mutton Bird	1.29 seconds (Range 1.13 - 1.47) Mean of 5 calls	Measurements of fundamental:- Mean of 5 starts 279 cps (225 - 315) Mean of 5 peaks 419 cps (270 - 500) Mean of 5 ends 297 cps (180 - 360) There are usually 2 harmonics	Call varies from a low moan to a harsh snarl
Leach's Petrel Flight call	1.02 seconds (Range .8 - 1.2) Mean of 5 calls	88 to over 8800 cps with most sound energy between 615 and 4100 cps	A series of 10 or 11 rapidly emitted notes, usually in the following pattern:- 
Leach's Petrel Burrow call	2.5 seconds between clucks (1 call measured)	Purring: up to 6500 cps with most sound energy below 2200 cps in a harmonic pattern. Ascending sound: 250-570 cps. Cluck: 88 to over 8800 cps in a harmonic pattern	A prolonged purring interrupted periodically (after 56 notes in one case) by the ascending sound of indrawn breath and a sharp cluck

Nesting

The nesting season of the Wedge-tailed Shearwater varies in the different parts of its extensive latitudinal range. In the northern colonies the time is in the northern spring, while in the southern Pacific it is in the southern spring (Murphy, 1951).

At Heron Island the first bird was seen on October 8th and the first egg on December 15th. Egg-laying was at its height at the end of December. The incubation period of the Wedge-tailed Shearwater is somewhat less than two months, while fledging requires at least three months, according to Oliver (1955).

We are indebted to Mr. H. F. Manning for information concerning the status of the shearwaters on Heron Island after our departure. A few of the adult birds left in March, 1961, but most of the adults do not usually leave until May. The birds are extremely noisy before their departure, and on the following day all is deathly quiet. The young are deserted in their burrows, where they remain until they are able to shift for themselves.

The Short-tailed Shearwater does not acquire sexual maturity until six or more years of age (Serventy, 1956b). As a similar period may exist for the Wedge-tailed Shearwater, a large portion of the birds present on Heron Island may be non-breeding individuals.

Summary

Wedge-tailed Shearwaters nesting at Heron Island were observed from their arrival on October 8, 1960, until January 1, 1961. Measurements of five unsexed living specimens and ten eggs were obtained. Widespread egg-laying began abruptly on December 15th. Many eggs were laid on the ground, but were not incubated. Nest-building, nightly arrivals and departures, courtship, copulation, and calls were observed and described. Sound spectrograms of the calls were compared with those of another tube-nose, Leach's Petrel, and found to be much simpler and less variable.

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Captions of Photos

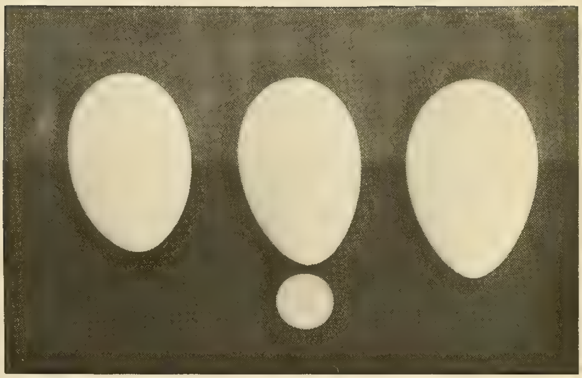
Upper left-- A characteristic pose of the Wedge-tailed Shearwater with its body resting flat on the ground. The crossed wing tips extend to near the end of the tail.

Upper right-- The Wedge-tailed Shearwater at left approaching its mate, which has just emerged from the nesting burrow.

Lower Left-- The shearwater at the left has approached its mate which has come out of the nesting burrow. The birds are billing each other and running their beaks through the feathers of the neck, a part of the courtship performance.

Lower right-- Three eggs of the Wedge-tailed Shearwater (Numbers 1-3 of Table II) with an Australian sixpence, showing the relative size of the large eggs.



ATOLL RESEARCH BULLETIN

No. 100

Atoll News and Comments

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ATOLL NEWS AND COMMENT

As announced previously, we are happy to continue this series which has the aim of keeping the ARB audience informed on current investigations on coral reefs and atolls, new books and other published items of particular interest in this connection, older published items to which it seems desirable to direct attention, and happenings of geneal interest to research workers in the field of reefs and atolls. The editors will be glad to receive notes or reviews of the above sorts from readers of the Bulletin which they feel will be of interest to their colleagues.

Atoll Investigations

Society Islands:

Expedition to Mopelia and Bora Bora:

In continuation of the program of investigation of Pacific coral reefs by the Centre National Français de la Recherche Scientifique and the Mission Singer-Polignac, a French expeidtion spent the last part of July and the first several weeks in August on the atoll of Mopelia or Mopiha'a in the Society Islands, then continued its work with a visit to the high island of Bora Bora, also in the Society Islands. It may be remembered that it was a visit to the latter island that furnished Charles Darwin with some of the information that led to the formulation of his subsidence theory of atoll formation.

Our correspondent Professor Andre Guilcher, of the Sorbonne, Professor François Doumenge, of the University of Montpelier, Professor Leopold Berthois, of l'École Nationale Agronomique, Rennes, and M. René Arnold, diver, underwater photographer and amateur zoologist, came from France, and were joined in Tahiti by the junior editor of ARB, Dr. Marie-Hélène Sachet, who was enroute to an investigation in the Marquesas. They were transported to Mopelia on "La Bayonnaise , French naval vessel based at Tahiti, and had at their disposal while on the atoll the small naval craft, "La Coralline

The main objectives of the expedition were to study the reefs from a geomorphological viewpoint, to sample the bottom sediments by means of a Peterson grab sampler, to study the properties of the lagoon water, and to study the land flora and vegetation of the islets of Mopelia. To the best of our knowledge no systematic attempt has previously been made to collect the land plants of this atoll and no description ever made of its vegetation.

After completion of the work on Mopelia, the expedition moved to Bora Bora, where the oceanographers and geologists studied its reefs and lagoon for comparison with those of Mopelia, while Dr. Sachet returned to Tahiti enroute to the Marquesas. We hope to have a more comprehensive account of the expedition and its results in a later number of the Bulletin.

Melanesian Atolls:

The "Noona Dan" Expedition.

"During the period August 1961 - September 1962 the motorketch "Noona Dan" has completed a cruise in Indo-Pacific waters under the auspices of the Copenhagen University, Denmark. The expedition was sponsored mainly by private donors (especially the Lauritzen-line), partly by official funds.

"The work of the expedition was concentrated in 3 main areas:

1) The islands in Southern Philippines (Balabac, Tawi-Tawi, Palawan, Ursula and Mindanao, visited in the period 12th August - 22 December 1961).

2) The Bismarck Archipelago (Mussau, Dyaul, Lavongai, Tingwon, central part of New Ireland, Gazelle Peninsula and Cape Hoskins area of New Britain, Manus in the Admiralty Group; all visited in the period 12th January - 13th July)

3) Rennell Island in the Solomon Group. 16th August - 3rd September 1962 (some of the expedition-members working on Bellona Island stayed there for another month).

Aside from Rennell short visits were paid to other atolls: Kilinailau, Nuguria, Tauu, Nukumanu. Additionally a trip was made to the Hermit Islands (quasi-atoll).

"Main task of the expedition was to collect samples representing animal and plant life in the areas mentioned (only land and freshwater species to be considered) with the intention of providing collections supplementing those made by previous marine expeditions. It was tried to concentrate work on small, isolated islands, so establishing a material that could shed some light on biological evolution and possibly contain hitherto unknown species. Especially insects, small reptiles, small mammals and birds were collected. Methods yielding quantitative results were always preferred. Beside this, work was carried out on other topics; thus types of soil were gathered by the botanists to support the ecological analyses.

"Apart from the biological work investigations of the marine terraces of the coralline islands of the Bismarck Archipelago were made. In the last phase of the expedition ethnographical research was included, mainly embracing subjects of religious and social life.

"Accomodations of the ship being limited, only up to six scientists were employed at the same time. The scientific leaders were:

"Dr. Børge Petersen, dr. Mogens Køie, dr. Finn Salomonsen and dr. Torben Wolff. The scientific staff: S. Andersen, L. Christensen, S. Christiansen, H. Dissing, L. Ferdinand, L. Lineborg, T. Monberg

Y. Sandermann-Olsen - assisted by W. Cuch, I. Trap Lind and E. Petersen. Unhappily the last mentioned lost his life by an accident during the expedition. As a very popular guest, professor Samuel Elbert, University of Hawaii, U.S.A. participated in the Rennell trip.

"Large collections have been the result of the expedition. Until now papers on new species and on some new races of birds have been published."

by Dr. Sofus Christiansen

Phoenix Islands:

Harry Maude writes: "I now hear that the whole of the population of the Phoenix Islands is being removed to the Solomon Islands owing to the prolonged drought. On Gardner Island the coconut supply is completely exhausted, nearly all the trees are dying and all the wells turned brackish except one in January." One wonders if the fact that these islands have always remained uninhabited should not have suggested an exhaustive ecological study before these colonies were established and people moved there.

Christmas Island:

Dr. Philip Helfrich continued his investigations of the marine biology of Christmas Island during the summer of 1963.

Wake Island:

Mr. Robert H. Alexander, Dr. M.-H. Sachet, and Dr. F. R. Fosberg made a brief stop at Wake Island in March, 1963, to see if any effects were still identifiable of the typhoon that devastated the island in 1952. A full report is expected in a future issue of the ARB.

Leeward Hawaiian Islands:

Kermit Gordon, director of the U. S. Bureau of the Budget, is said to be reconsidering his decision to turn the Hawaiian Islands National Wildlife Refuge over to the State of Hawaii after a storm of protest from conservationists who have no faith in the conservation policies of the State of Hawaii.

Gilbert and Ellice Islands:

William Briggs, of the U. S. Geological Survey, was able to collect for a few hours on Funafuti, Ellice Is., and Onotoa, Gilbert Is., during rest stops on a Scripps oceanographic cruise in 1962.

Dr. Gerd Koch writes that he has reached the Gilbert Islands (see ARB 94, pp. 14-15) and was at work at the time of writing, August 17, 1963, at Niutao.

Caroline Islands:

Dr. Vern Carroll writes: "Vern Carroll, a graduate student in anthropology at the University of Chicago, has been awarded a research grant by the National Institute of Mental Health to study the social organization of Nukuoro Island, U. S. Trust Territory of the Pacific Islands for a period of eighteen months. Mr. Carroll, who received his undergraduate training in anthropology at Yale University and who has received graduate degrees from Yale and from Cambridge, will be principally concerned with the local systems of descent, inheritance and succession to offices of leadership on this little-known atoll. He will also investigate the means by which increase in population was controlled in the past and study the ecological context of the contemporary society. Owing to the fact that Nukuoro is very nearly a blank spot on the ethnographic map. Mr. Carroll intends to devote a portion of his time to general ethnographic and linguistic inquiries. Any one with a research interest in this atoll is invited to communicate with him. The field period will begin in the summer of 1963."

New Books

Tuamotus and pearl oysters:

Missions dans le Pacifique; Recifs Coralliens, Huitres Perlieres. by Gilbert Ranson. i-viii, 1-1[illegible]0, 47 pls. 9 figs. Editions Paul Lechevalier, Paris. 1962.

Dr. Ranson's work in the Pacific, particularly in the region of the Tuamotus, is well known through the number of short papers which have appeared in the Comptes Rendus. His interests, as exhibited in these notes, have lately been in the role of calcareous algae and filamentous algae in the formation of coral reefs and coral islands, and in the biology of the pearl oyster, a monographic treatment of which group is in preparation.

In this little book Dr. Ranson accumulates much of the data he has previously published, but it is presented in a more popular fashion, although the style shifts from the pedantic to the florid. The principal purpose of the book is to present a setting for the discussions of economy and conservation of the pearl shell industry in French Oceania. Of the seven chapters, the first three deal with the physical attributes of the Tuamotus, the fourth treats the shell industry of French Oceania and a fifth mentions several observations on water color, and the two final chapters are essentially a tra el-log of visits to Viet Nam and Japan in particular relation to the shell industry of these areas.

In the first chapter, Dr. Ranson rightfully considers that modern reefs are but a veneer of live coral over fossil reefs, which is really only a restatement of the fact that time is required for the accumulation of the debris which is the reef. He concludes that Darwin's subsidence theory of atoll formation is the most satisfactory to account for all aspects of the Tuamotus. In commenting upon the role of algae in corrosion of limestones, Dr. Ranson takes to task the solution hypotheses of

MacNeil, Ladd, and Hoffmeister. The platform of the Tuamotus is considered to have been uplifted slowly, although the area of Makatea and Niau near the edge of the platform has been subjected to a more violent uplift. The 1.8 m. terrace of the Pacific is recognized. The chapter, which presents no new information or synthesis, is marred by the absence of bibliographic citations.

The second chapter, which deals with factors involved in the solution of limestone, considers largely the effects of algae upon corals and coral rock. Aside from slight corrosive and abrasive activity of other organisms, particularly echinoids, the algae are considered to be most important in solution activity. The role of calcareous algae in the formation of the Lithothamnium ridge and in the formation of "buttress and recess" structures is briefly discussed. The third chapter, dealing with phosphate occurrences on the high islands of the Tuamotus, contains Ranson's argument that the phosphates are essentially residual, formed from organic materials leached from the original limestone. Guano is discounted in the formation of these deposits. The chapter contains, almost as an afterthought, a few comments upon the consolidation of beach-rock.

The fourth chapter is the longest and deals with the pearl oyster shell industry in French Oceania. This over-exploited industry is reexamined and conservation methods are discussed. Most of the format is given to a transcription of discussions between leaders of the industry in Papeete and Dr. Ranson. Conservation and introduction of methods such as those utilized in Japan were put into practice in the Tuamotu lagoons, particularly the provision for substrate ideal for settlement of the spat.

The final chapters are a mixed lot. A short one deals with the cause of water coloration, and contains the interesting observation that milky water, observed by Ranson in the Tuamotus, is caused by a mucus secretion containing finely disseminated calcium carbonate particles emitted by Cardium. The final two chapters, as indicated above, deal with his travels in Viet Nam and Japan respectively and are principally oriented towards the pearl shell industry.

The book suffers from the absence of documentation of many ideans and an uneven citation of bibliographic references. These are lacking in chapter 1, fully cited in chapter 2, but are only partially given in chapter 3. The illustrations are in black and white and are of uneven quality and are mainly unimaginative in content. The cover is a handsome yellow with a color inset of a typical tropical scene.

by Donald F. Squires

Bikini and Eniwetok Tests:

Proving Ground, by N. O. Hines. 1-336, 64 photos, 14 maps, 3 charts, University of Washington Press, Seattle, 1962. $6.75.

This is an important book.. Although it purports to be merely a history of the Laboratory of Radiation Biology, of the University of Washington, and especially of its radiobiological studies in the Pacific between 1946

and 1961, the book contains an account of the early activities of the Atomic Energy Commission that relate to biology. As such it will serve as a source document when the time comes to weigh some of the activities, consequences, and responsibilities of the program of the AEC and its sponsored agencies. This is especially true since the book obviously was written and published under the sponsorship of the Laboratory of Radiation Biology and with the blessing of the AEC. Certainly no one may say that its content is prejudiced against these organizations or that the author was denied access to the full story.

Proving Ground is written in a very readable style. In fact, in places there is even created a feeling of urgency and suspense. It contains much factual inforaation of value even above and beyond the stated objectives of the book. It is liberally illustrated with beautifully reproduced photographs, as well as with maps, diagrams, and graphs, all of great interest to an audience concerned with coral atolls. The chronological story of the tests at Bikini and Eniwetok and the biological research that accompanied and followed them, at least that carried on by the University of Washington group, is very well told, indeed.

Well told, also, is the story of the Laboratory's struggle to survive and to do a job of a magnitude that probably even the personnel, themselves, did not fully appreciate, on the pittances doled out to them by an administration dominated by physicists and military men. There is evidence throughout the book of the remarkable parsimony on the part of the AEC in their support of field biological research, especially in the critical 1950-1952 period. The resources and staff were never nearly equal to the assignments they were given. And the assignments showed little appreciation of either the magnitude or the importance of the task of understanding the ramifications of the effects of the tests on the ecosystems involved, or of the possible effects on the human inhabitants of these systems (cf. pp. 87-88, 102-103, 125-132, 152).

One impression that persists and grows in the reader's mind throughout the book is of the stultifying effect on scientific work of too much planning and discussion. What has emerged, in many of the programs described, bears little resemblance to what seemed to be in mind when the program was proposed. Recognition of a good proposal and giving encouragement and support to the proposer, forthwith, to carry it out never seems to have occurred at the planning levels in the AEC, at least in the biological field. Everything seemed to be the products of composite mental efforts, with anything at all bold carefullyeliminated. Perhaps this is the modern way.

Against this background it is perhaps a bit easier to understand, if not to appreciate, the impression of coolness so often given by the Radiation Biology Laboratory personnel toward suggested incursions by outsiders into the Proving Ground picture, even a suggestion of proprietary feeling about the field of research on the biological results of testing in the Pacific atolls. AEC policies may also explain the apparent reluctance about prompt publication of the data collected by the numerous Laboratory expeditions.

This tightness has relaxed some in recent years, but there still seems a remarkable paucity of published information compared to the amount of research effort expended. It is good to be able to say that much information of a general character, or of possible popular interest, is made available, some of it for the first time, in the pages of the book under review. This is certainly the best available summary of the results of the work done in and around Bikini and Eniwetok by the Laboratory of Radiation Biology.

For this reason it seems proper to point out a very few errors, some of them of ommission, that have slipped by the obviously competent scientific reviewing that this volume has had. These are remarkably few in number, and some are possibly justifiable omissions.

On p. 31, the statement is made that the first drillings made to investigate the depths of coral beneath an atoll reef were those on Funafuti in 1897 and 1898. Actually, Capt. Belcher attempted a boring at Boring Bay, Hao Atoll, in the Tuamotus almost 60 years earlier.

In the account of the Crossroads Operation it is surprising to find no mention of the role of Lt. Cmdr. Roger Revelle, USN, in initiating the scientific survey.

One may at least question the correctness of the statement on p. 165 that the Bravo Shot produced the first "mishap and human suffering, the first such results attributable to the test program." This, it seems, ignores the whole question of the dislocation and maladjustment suffered by the people of Bikini, who were uprooted from their homes and removed so that their island could be used for the tests.

On p. 267, third line from the bottom, a word must have been omitted after "American".

In the list of plants on p. 324 Portulaca quadrifida is included. This species is not known in the Pacific east of Guam. Probably Portulaca samoensis is the species in question.

On p. 309, one cannot positively quarrel with the statement, "The probabilities of remote radiation effects could not be denied, but positive evidence of such effects was not found at the test atolls or anywhere else in the Pacific," but one wonders if this could not be because of not knowing what to look for, or not recognizing it or interpreting correctly what was found.

This book is recommended without hesitation to those interested in coral atolls, and Neal Hines is to be congratulated on his remarkable success in telling a scientific story in a way that is at once readable, informative, and scientifically sound.

Rats:

Pacific Island Rat Ecology, edited by Tracy I. Storer, and containing papers by the members of the Pacific Science Board team which worked in

Micronesia from 1955 to 1958, was recently published as Bishop Museum Bulletin 225, issued Dec. 31, 1962. The papers deal mainly with Ponape, a high island, but some of the work was done on atolls--Majuro, Ant, and Oroluk, and there are records of several kinds of rats from these atolls, as well as descriptions, photos, and ecological notes. This volume is a commendable example of integration of the results obtained by four ecologists, Robert L. Strecker, Joe T. Marshall, Jr., William B. Jackson, and Kyle R. Barbehenn, and the work of a systematic mammalogist, David H. Johnson, ably directed by Tracey I Storer, world renouned animal ecologist, who also edited the book. It is a noteworthy addition to the growing literature on the ecology of the Pacific islands.

Indian Ocean Birds:

Watson, G. E. Zusi, R. L., and Storer, R. E., Preliminary Field Guide to the Birds of the Indian Ocean, 214 pp., was published by the Smithsonian Institution in 1963. This interesting book was prepared especialy for the use of the personnel of the International Indian Ocean Expedition. It contains directions for making collections and observations on birds; a list of all the birds known from the area, with their distribution; alphabetical lists of Latin and English names; field identification plates for each group of birds, illustrating the species with their principal identification marks indicated, and a brief statement of identifying features in the captions for these, and lists of birds found on the principal islands and island groups, these shown on a small map and on larger maps for individual islands and groups. This is a valuable compilation of distributional information, and is of interest to atoll students both because of the numerous atolls in the Indian Ocean area treated and because many of the birds found there are widely distributed on atolls in other oceans. Atolls and atoll groups treated are Cocos-Keeling, Laccadives, Minicoy, Maldives, Chagos Archipelago, Cargados Carajos, Tromelin, Platte, Coetivy, Bird, Dennis, Agalega, Amirantes, Providence, St. Pierre, Farquhar, Cosmoledo, Astove, and Gloriosa. The area covered by the book includes most of the islands in the Indian Ocean, but excludes Madagascar, Sokotra, Ceylon, the Andamans, The Nicobars, and the islands lying west of Sumatra and Australia. The continental rim, also, is excluded.

Recent Deaths

David I. Blumenstock: It is with sadness and regret that we record the untimely death of our friend, colleague, and contributor to the Atoll Research Bulletin, Prof. David Blumenstock, on August 28, 1963. Although only 49 at the time of his death, Dave had, for years, exhibited a mature grasp of his field of climatology seldom attained by a man of 60. An expert in his own field, he was also outstanding as a generalist, and as such, it is appropriate that he ended his career as a member of the University of California Geography Department. His book Ocean of Air, though written as a popularization of meteorology, should be required reading for ecologists and geographers. It is not only competently written, it is a pleasure to read.

He first came to us in 1955, when moving from Rutgers, New Jersey, to Honolulu, where he was to be climatologist for the Pacific region, U. S. Weather Bureau. He wanted to know what were the problems where a climatologist could be useful to biologists in the Pacific Islands. We suggested a study of the effects of typhoons on islands and their vegetation and other life. He followed this lead and ranged the Pacific very widely, studying the aftermaths of typhoons. A brief look at the immediate effects of Typhoon Ophelia on Jaluit Atoll, in January 1958, led him to organize an expedition several months later to study this storm's behavior, the results of which were presented in ARB No. 75. The notes taken on a second expedition to Jaluit, two years later, and on another expedition to Ulithi, after a typhoon had raked that large atoll, have not been published. It is sincerely hoped that his great accumulation of information on this subject can be salvaged and made available, as he would have wanted.

His place in the Pacific Islands scientific community will not easily be filled.

Carl L. Skottsberg: We also regret to have to record the death of Prof. Carl Skottsberg, in Gothenburg, Sweden, on June 14, 1963. He did not work directly on any atoll, so far as we know, but contributed probably more than anyone else to the over-all phytogeographical picture of the Pacitic Islands during his sixty-odd years of active botanical work.

Joseph Rock: Death of another Pacific botanist, Dr. Joseph Rock, took place in Honolulu on December 5, 1962, according to the Newsletter of the Hawaiian Botanical Society, vol. 2, no. 1. He visited Palmyra Island in 1913 and published the first account of its flora and vegetation in 1916. A biographical sketch, by Alvin K. Chock, appears in the cited number of the Newsletter, and also in Taxon, vol. 12, pages 89-102, 1963.

Matters of General Interest

Pacific Botanists 1963:

The Pacific Scientific Information Center has recently published "Pacific Botanists 1963", a revision of earlier lists of botanists interested in Pacific Basin problems prepared by the Standing Committee for Pacific Botany. This list is arranged alphabetically, but is accompanied by an extensive "Interest Index" which lists the botanists by subject and geographical interests, and by a "Residence Index" which lists them by country of residence. The files on which this index is based, transferred to the Information Center by the Standing Committee for Pacific Botany, are kept permanently open for revision and addition, and corrections are solicited. This index follows the similar "Pacitic Anthropologists 1962".

Micronesica:

The College of Guam has announced the founding of Micronesica, a new scientific journal to be devoted to all branches of science and including

papers from Micronesia and related areas. The editor-in-chief is Dr. Benjamin C. Stone, of the Botany Department, College of Guam, assisted by a number of associate editors for different subjects. Manuscripts are welcome and should be sent to Dr. B. C. Stone, Editorial Office, Micronesica, College of Guam, Box 97, Guam, U.S.A. It is hoped that the first number may appear by June, 1964.

Hawaiian Botanical Society Newsletter:

The Hawaiian Botanical Society Newsletter, inaugurated in February 1962, is now in its second year of publication. This mimeographed publication is issued monthly except during the months of July, August, and September, and includes articles and notes of general interest about Hawaiian and Pacific Botany and a list of recent publications. The Society's annual membership fee of $2.00 includes receipt of the newsletter. Newsletter correspondence should be sent to the Editor (Alvin K. Chock, B. P. Bishop Museum, Honolulu 17, Hawaii) or the Assistant Editor (Tosho Murashige, Department of Horticulture, University of Hawaii, Honolulu 14, Hawaii).

Another Bomb Test:

We are informed that the French have selected the atoll of Mururoa, in the southern Tuamotus, to test a hydrogen bomb, probably in 1965. At present they are said to be building air strips on Anaa and Hao, for use in this enterprise. We hope that, if they proceed with this misguided enterprise, they will at least carry out a thorough scientific survey of the atoll before everything is irretrievably destroyed. We will try to get a more complete account of this project for a later number.

Contributions:

We have tried to acknowledge the many contributions received toward the publication fund of the Bulletin, but may have missed some. We sincerely appreciate this support, both because it is needed, and because it shows that the Bulletin is useful and appreciated. Future contributions will also be extremely welcome.

List of Atoll Research Bulletins 1-100

1. Basic information papers, by various authors. 1-25, Sept. 10, 1951.

2. Symposium on coral atoll research, by various authors. 1-14, Sept. 10, 1951.

3. Vertebrate ecology of Arno Atoll, Marshall Islands, by J. T. Marshall, Jr. 1-38, Oct. 15, 1951.

4. Marine zoology study of Arno Atoll, Marshall Islands, by R. W. Hiatt and D. Strasburg. 1-13, Oct. 15, 1951.

5. The soils of Arno Atoll, Marshall Islands, by E. L. Stone, Jr. 1-56, Nov. 15, 1951.

6. The agriculture of Arno Atoll, Marshall Islands, by E. L. Stone, Jr. 1-46, Nov. 15, 1951.

7. The plants of Arno Atoll, Marshall Islands, by D. Anderson. 1-4, i-vii, Nov. 15, 1951.

8. The hydrology of Arno Atoll, Marshall Islands, by D. C. Cox. 1-29, Dec. 15, 1951.

9. The coral reefs of Arno Atoll, Marshall Islands, by J. W. Wells. 1-14, Dec. 15, 1951.

10. Anthropology-geography study of Arno Atoll, Marshall Islands, by L. Mason, J. Tobin and G. Wade. 1-21, Sept. 1, 1952.

11. Land tenure in the Marshall Islands, by J. Tobin. 1-36, Sept. 1, 1952.

12. Preliminary report on geology and marine environment of Onotoa Atoll, Gilbert Islands, by P. E. Cloud, Jr. 1-73, Dec. 15, 1952.

13. Preliminary report on marine biology study of Onotoa Atoll, Gilbert Islands, by A.H. Banner and J.E. Randall. 1-62, Dec. 15, 1952.

14. Description of Kayangel Atoll, Palau Islands, by J.L. Gressitt. 1-6, Dec. 15, 1952.

15. The insect life of Arno, by R. L. Usinger and I. La Rivers. 1-28, April 30, 1953.

16. The land vegetation of Arno Atoll, Marshall Islands, by W. H. Hatheway. 1-68, April 30, 1953.

17. Handbook for atoll research, by various authors, edited by F. R. Fosberg and Marie-Hélène Sachet. 1-129, May 15, 1953.

18. Ichtyological field data of Raroia Atoll, Tuamotu Archipelago, by R. R. Harry. 1-190, July 31, 1953.

19. Check list of atolls, by E. H. Bryan, Jr. 1-38, Sept. 30, 1953.

20. Health report of Kapingamarangi, by R. E. Miller. 1-42, Sept. 30, 1953.

21. Notes on Ngaruangl and Kayangel Atolls, Palau Islands, by J. L. Gressitt. 1-5, Sept. 30, 1953.

22. Summary of information on atoll soils, by E. L. Stone, Jr. 1-4, Sept. 30, 1953.

23. Vegetation of Central Pacific Atolls, a brief summary, by F. R. Fosberg. 1-26, Sept. 30, 1953.

24. Enumeration of the decapod and stomatopod Crustacea from Pacific coral islands, by L. B. Holthuis. 1-66, Nov. 15, 1953.

25. Bryophytes from Arno Atoll, Marshall Islands, by H. A. Miller and M. S. Doty. 1-10, Nov. 15, 1953.

26. Scorpions on coral atolls, by M.-H. Sachet. 1-10, Nov. 15, 1953.

27. Nutrition study in Micronesia, by M. Murai. 1-239, Jan. 31, 1954.

28. Preliminary report on land animals at Onotoa Atoll, Gilbert Islands, by E. T. Moul. 1-28, May 31, 1954.

29. A summary of information on Rose Atoll, by M.-H. Sachet. 1-25, May 31, 1954.

30. The hydrology of the Northern Marshall Islands, by T. Arnow. 1-7, May 31, 1954.

31. Expedition to Raroia, Tuamotus, Part 1. Expedition to Raroia, Tuamotus, by N. D. Newell. 1-12; Part 2. Physical characteristics of Raroia, by N. D. Newell. 13-21; Part 3. General map of Raroia Atoll, by N. D. Newell. Nov. 30, 1954.

32. Raroian Culture, Part 1. Economy of Raroia Atoll, Tuamotu Archipelago, by B. Danielsson. 1-91; Part 2. Native topographical terms in Raroia, Tuamotus, by B. Danielsson. 92-96; Part 3. Native terminology of the coconut palm in Raroia Atoll, by B. Danielsson. 97-99; Part 4. Bird names in Raroia Atoll, by B. Danielsson and A. Natua. 100-101; Part 5. Check list of the native names of fishes of Raroia Atoll, by B. Danielsson. 102-109. Nov. 30, 1954.

33. Floristics and plant ecology of Raroia Atoll, Tuamotus, Part 1. Floristic and ecological notes on Raroia, by M. S. Doty. 1-41; Part 2. Ecological and floristic notes on the Myxophyta of Raroia, by J. Newhouse. 42-54; Part 3. Ecological and floristic notes on the Bryophyta of Raroia, by H. A. Miller and M. S. Doty. 55-56; Part 4. Ecological and floristic notes on the Pteridophyta of Raroia, by K. Wilson. 57-58, Nov. 30, 1954.

34. Animal ecology of Raroia Atoll, Tuamotus, Part 1. Ecological notes on the mollusks and other animals of Raroia, by J. P. E. Morrison. 1-18; Part 2. Notes on the birds of Raroia, by J. P. E. Morrison, 19-26. Nov. 30, 1954.

35. Interrelationship of the organisms on Raroia aside from man, by M. S. Doty and J. P. E. Morrison. 1-61. Nov. 30, 1954.

36. Reefs and sedimentary processes of Raroia, by N. D. Newell. 1-35, Nov. 30, 1954.

37. Pumice and other extraneous volcanic materials on coral atolls, by M.-H. Sachet. 1-27, May 15, 1955.

38. Northern Marshall Islands Expedition, 1951-1952. Narrative by F. R. Fosberg. 1-36, May 15, 1955.

39. Northern Marshall Islands Expedition, 1951-1952. Land biota: Vascular plants, by F. R. Fosberg. 1-22, May 15, 1955.

40. Bryophytes collected by F. R. Fosberg in the Marshall Islands, by H. A. Miller. 1-4, May 15, 1955.

41. Canton Island, South Pacific, by O. Degener and E. Gillaspy. 1-51, Aug. 15, 1955.

42. The insects and certain other arthropods of Canton Island, by R. H. Van Zwaluwenburg. 1-11, Aug. 15, 1955.

43. The natural vegetation of Canton Island, an equatorial Pacific atoll, by W. H. Hatheway. 1-9, Aug. 15, 1955.

44. The hydrology of Ifalik Atoll, Western Caroline Islands, by T. Arnow. 1-15, Aug. 15, 1955.

45. A partial list of the plants of the Midway Islands by J. A. Neff and P. A. DuMont. 1-11, Aug. 15, 1955.

46. Conspicuous features of organic reefs, by J. I. Tracey, Jr., P. E. Cloud, Jr. and K. O. Emery. 1-3, Aug. 15, 1955.

47. Fishes of the Gilbert Islands, by J. E. Randall. 1-243, Aug. 15, 1955.

48. The geography of Kapingamarangi Atoll in the Eastern Carolines, by Herold J. Wiens. 1-86, 1- [7], June 30, 1956.

49. Bioecology of Kapingamarangi Atoll, Caroline Islands: Terrestrial aspects, by William A. Niering. 1-32, June 30, 1956.

50. Geology of Kapingamarangi Atoll, Caroline Islands, by Edwin D. McKee. 1-38, June 30, 1956.

51. Observations on French Frigate Shoals, February 1956, by Arthur Svihla. 1-2, Sept. 15, 1957.

52. Zonation of corals on Japtan Reef, Eniwetok Atoll, by Eugene P. Odum and Howard T. Odum. 1-3, Sept. 15, 1957.

53. Slicks on ocean surface downwind from coral reefs, by F. R. Fosberg. 1-4, Sept. 15, 1957.

54. Field notes on atolls visited in the Marshalls, 1956, by Herold J. Wiens. 1-23, September 15, 1957.

55. Agricultural notes on the Southern Marshall Islands, 1952, by W. H. Hatheway. 1-9, September 15, 1957.

56. Atolls visited during the first year of the Pacific Islands Rat Ecology Project, by J. T. Marshall, Jr. 1-11, Sept. 15, 1957.

57. Preliminary report on the flora of Onotoa Atoll, Gilbert Islands, by Edwin T. Moul. 1-48, September 15, 1957.

58. The Maldive Islands, Indian Ocean, by F. R. Fosberg. 1-37, September 15, 1957.

59. Report on the Gilbert Islands: Some aspects of human ecology, by René L. A. Catala. 1-187, October 31, 1957.

60. Climate and Meteorology of the Gilbert Islands, by M.-H. Sachet. 1-4, October 31, 1957.

61. Long-term effects of radioactive fallout on plants, by F. R. Fosberg. 1-11, May 15, 1959.

62. Health and sanitation survey of Arno Atoll, by J. D. Milhurn. 1-7, May 15, 1959.

63. Report on a visit to the Chesterfield Islands, September, 1957, by F. Cohic. 1-11, May 15, 1959.

64. Canton Island, South Pacific (Resurvey of 1958), by Otto Degener and Isa Degener. 1-24, May 15, 1959.

65. Some marine algae from Canton Atoll, by E. Yale Dawson. 1-6, May 15, 1959.

66. Notes on the geography and natural history of Wake Island, by E. H. Bryan, Jr. 1-22, May 15, 1959.

67. Vegetation and flora of Wake Island, by F.R. Fosberg. 1-20, May 15, 1959.

68. Additional records of phanerogams from the northern Marshall Islands, by F. R. Fosberg. 1-9, May 15, 1959.

69. Contribution to a German reef-terminology, by Georg Scheer. 1-4, May 15, 1959.

70. Atoll news and comment, Editors. 1-7, May 15, 1959.

71. Microclimatic observations at Eniwetok, by David I. Blumenstock and Daniel F. Rex, with a special section on Vegetation by Irwin E. Lane. i-ix, 1-158, June 30, 1960.

72. Report on Tarawa Atoll, Gilbert Islands, by Edwin Doran, Jr. 1-54+24, October 15, 1960.

73. Some aspects of Agriculture on Tarawa Atoll, Gilbert Islands, by R. R. Mason. 1-17, October 15, 1960.

74. Birds of the Gilbert and Ellice Islands Colony, by Peter Child, 1-38 October 15, 1960.

75. A report on Typhoon Effects upon Jaluit Atoll edited, by David I. Blumenstock. 1-105, April 15, 1961.

76. Observations on Puluwat and Gaferut, Caroline Islands, by William A. Niering. 1-10, December 31, 1961.
Historical and climatic information on Gaferut Island, by Marie-Hélène Sachet. 11-15, December 31, 1961.

77. A check list of marine algae from Ifaluk Atoll, Caroline Islands, by Isabella A. Abbott. 1-5, December 31, 1961.

78. Narrative report of botanical field work on Kure Island, 3 October 1959 to 9 October 1959, by Horace F. Clay. 1-4, December 31, 1961.

79. Botanical observations on Leeward Hawaiian Atolls, by Charles H. Lamoureux. 1-10, December 31, 1961.

80. The tropical coral reef as a biotope, by Sebastian A. Gerlach. 1-6, December 31, 1961.

81. Qualitative description of the coral atoll ecosystem, by F. R. Fosberg. 1-11, December 31, 1961.

82. Heron Island, Capricorn Group, Australia, by F. R. Fosberg, R. F. Thorne and J. M. Moulton. 1-4, 5-13, 15-16, December 31, 1961.

83. Notes on some of the Seychelles Islands, Indian Ocean, by C. J. Piggott. 1-10, December 31, 1961.

84. Atoll News and Comments. Editors, 1-14, December 31, 1961.

85. Land tenure in the Pacific - A symposium of the Tenth Pacific Science Congress convened by Edwin Doran, Jr. 1-60, December 31, 1961.

86. Geography and land ecology of Clipperton Island, by Marie-Hélène Sachet. 1-115, February 28, 1962.

87. Three Caribbean atolls: Turneffe Islands, Lighthouse Reef, and Glover's Reef, British Honduras, by D. R. Stoddart. 1-151, June 30, 1962.

88. Coral Islands, by Charles Darwin, with introduction, map and remarks by D. R. Stoddart. 1-20, Dec. 15, 1962.

89. Geophysical observations on Christmas Island, by John Northrop. 1-2, Dec. 15, 1962.

90. Plants of Christmas Island, by Alvin K. Chock and Dean C. Hamilton, Jr. 1-7, December 15, 1962.

91. Central subsidence. A new theory of atoll formation, by Hans Hass. 1-4, Dec. 15, 1962.

92. Vascular plants recorded from Jaluit Atoll, by F. R. Fosberg and M.-H. Sachet. 1-39, Dec. 15, 1962.

93. A brief study of the cays of Arrecife Alacran, a Mexican atoll, by F. R. Fosberg. 1-25, Dec. 15, 1962.

94. Atoll news and comments, Editors, 1-19, Dec. 15, 1962.

95. Effects of Hurricane Hattie on the British Honduras Reefs and Cays, October 30-31, 1961, by D. R. Stoddart. 1-142, May 15, 1963.

96. Some aspects of the meteorology of the tropical Pacific viewed from an atoll, by Ronald L. Lavoie. 1-80, May 15, 1963.

97. The flora and vegetation of Laysan Island, by Charles H. Lamoureux. 1-14, November 15, 1963.

98. Insects and other invertebrates from Laysan Island by George D. Butler, Jr., and Robert L. Usinger. 1-30, November 15, 1963.

99. Notes on the Wedge-tailed Shearwater at Heron Island, Great Barrier Reef, Australia, by A. O. Gross, J. M. Moulton and C. E. Huntington. 1-11, November 15, 1963.

100. Atoll news and comments, Editors. 1-16, November 15, 1963.

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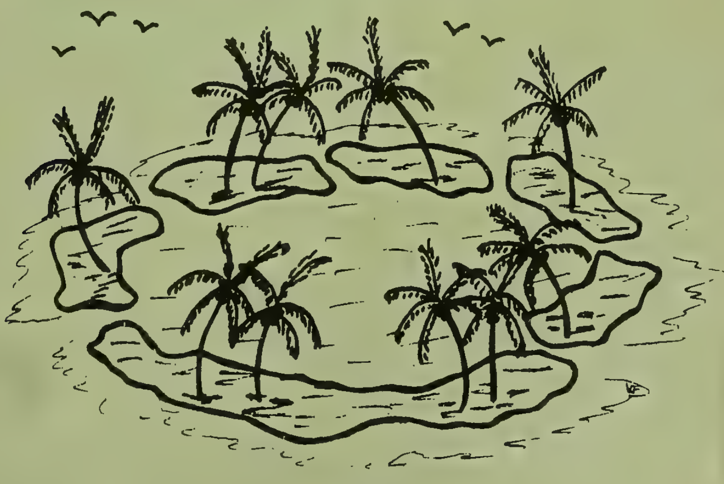
ATOLL RESEARCH BULLETIN



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ACKNOWLEDGMENT

It is a pleasure to commend the far-sighted policy of the Office of Naval Research, with its emphasis on basic research, as a result of which a grant has made possible the continuation of the Coral Atoll Program of the Pacific Science Board.

It is of interest to note, historically, that much of the fundamental information on atolls of the Pacific was gathered by the U. S. Navy's South Pacific Exploring Expedition, over one hundred years ago, under the command of Captain Charles Wilkes. The continuing nature of such scientific interest by the Navy is shown by the support for the Pacific Science Board's research programs during the past fifteen years.

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ATOLL RESEARCH BULLETIN

No. 101

Notes on Indian Ocean atolls visited by the Yale Seychelles Expedition

by

Alan J. Kohn

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Notes on Indian Ocean atolls visited by the Yale Seychelles Expedition

by

Alan J. Kohn[1]

I. The Maldive Islands, with special reference to the coral reefs

The Yale Seychelles Expedition vessel 'Argosy', a 110-foot ketch (Fig. 1), left Colombo 15 September 1957 and entered the lagoon of North Male Atoll on 19 September. The 37-foot fishing cruiser 'Sea Quest' also participated in the Expedition. The scientific staff of three zoologists included Dr. James E. Morrow, Jr., chief scientist (fishes); Dr. Willard D. Hartman (sponges); and the writer (molluscs). The expedition was made possible through the generosity of Mr. Alfred C. Glassell, Jr.

The following notes are taken from the writer's field notebooks. Horizontal distances are given in metric units, but water depths and other vertical distances are in feet to conform with U.S.C.G.S. Tide Tables. In all cases, tidal datum is mean low water springs (MLWS). The few sea temperatures recorded are given in Table 1. For more extensive accounts of the Maldive Islands, reference may be made to Gardiner (1903) and Agassiz (1903).

North Male Atoll

Funidu (YSE Sta. 17)

Following a visit to the main island of Male (described by Villiers, 1957), several days were devoted to surveying the invertebrate fauna of a well-developed coral reef fringing a small island within the lagoon, called Funidu by the Maldivians but unnamed on charts (Fig. 2). A separate report on this study is given in Atoll Research Bulletin 102.

Dunidu (YSE Sta. 18)

Further collections of reef fauna were made at Dunidu I., also entirely within the lagoon. A large tide pool on the east side of the island was poisoned with rotenone for collection of fishes and invertebrates. The shore on this side was mainly of beachrock. An old British rest house on Dunidu provided lodging and laboratory space for Dr. Hartman and myself for four days (5-8 October). During this time we were able to make limited collections of shore invertebrates at night.

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[1] Department of Zoology, University of Washington.

Hulule (YSE Sta. 22)

J.S. Gardiner spent a month on Hulule in 1900, but described the island only briefly (1903: p. 7, 329 ff.). We made two trips to the seaward reef opposite the east side of the island. The reef is extremely broad, 400 m on the chart, but of this the inshore ca. 350 m is a uniform sand flat at about -1'. Near the outer edge, coral and coral rubble increase in abundance. In some areas in the surge zone the blue alcyonarian coral Heliopora is extremely abundant, as it was during Gardiner's visit (1903: p. 477). Extensive areas of flat reef limestone pavement near the outer edge are covered with large chunks of coral rubble, apparently thrown up by waves from the outer reef face (Figs. 3, 4).

A few habitat notes on the molluscs collected were made: In the sandy areas, only a few small specimens of three species of Terebra and a number of empty pelecypod shells were collected. Near the outer edge, several species of Cypraea occurred under coral heads and rubble. C. moneta was common in coral rocks and large pieces of rubble. Cantharus sp. and a large Thais sp. were very common but not collected. Tridacna up to 35 cm in length were also abundant. The species of Tridacna are extremely difficult to determine in the field, and a few of each morphological type were collected. The second collecting trip concentrated in the rubble and coral zone opposite the north end of Hulule. Engina sp. was the dominant mollusc, but members of this phylum were sparser here than on any other reef visited in the Maldives. Gardiner (1903: p. 7) also observed that "Mollusca are not numerous" at Hulule.

While collecting at Hulule, we were joined by many Maldivian children. By placing the entire coral head in the opened sarong and lifting it out of the water, they ingeniously catch reef fishes that dart back into coral heads when startled.

Male (YSE Sta. 23)

Collections were made chiefly along the outer edge of the reef flat on the west side of Male I., the eastern edge of the channel between Male and Wilingili. The outer edge slopes rather gently across a zone of living and dead coral heads about 20 m wide to ca. -2' at the steep reef face. This zone was characterized by abundant Cypraea tigris, which is abundant only in scattered locations in the Maldives. The inshore edge of this zone is shallow, about the +1' level, and covered with dead coral and rubble. The broad reef flat from the rubble zone to shore, about 100 m wide, is at about the +0.5' level and covered with a dense mat of turtle grass (Thalassia?) and algae. Sponges were abundant.

Fadiffolu Atoll

In company with the Maldives' official guide, Mr. L. Ibrahim Didi 'Argosy' left Male for Fadiffolu Atoll 24 September and arrived at Naifaro ("prawn reef") Island the following morning. The population of Fadiffolu is about 4,000, most of whom live on Naifaro, a large fishing village, and Inawari. Naifaro boasts several 2-story buildings.

Kuredu (YSE Sta. 20)

'Argosy' continued northeastward and anchored in the lagoon off Kuredu, a large island with a small village occupied permanently by only one family. We collected on the seaward reef at Kuredu 26-28 September. The reefs of Fadiffolu have been described by Gardiner (1903: pp. 396-402) and Agassiz (1903: pp. 73-77), but Kuredu is only mentioned briefly by Gardiner.

The seaward reef at Kuredu is about 300 m wide at the southern end of the island, where most of the collecting was done (Fig. 5), narrowing to a virtual absence of reef at the north end. The substrate of the landward half of the reef flat is almost completely sand. A number of completely buried gastropods were exposed by fanning the sand. These included five species of Terebra, 3 of Mitra, and 3 of Conus. About halfway across the reef sparse mainly dead Acropora colonies appear. To seaward, living Acropora and other corals become more abundant. At about 80% of the distance from shore to seaward edge is a shallow (at about the -1' level) zone of coral rubble, followed to seaward by low growing corals. The depth gradually increases, as does the height of the coral heads. At about -3', the bottom is smooth reef limestone between coral heads. This type of substrate slopes gently to seaward for about 50 m to the steep reef face, and blue water occurs to the west. Hence there is no algal ridge at the reef edge. About 120 species of molluscs, of which 17 were Pelecypoda, one an octopus, and the rest Gastropoda, were collected on the Kuredu reef.

On Kuredu are several large, brackish ponds, some of them quite deep. Dense populations of the gastropod Terebralia palustris occupy substratum. The ponds are probably remnants of a former velu, the lagoon of a faro or small atoll. Faros form the outer ring of the several composite atolls that are characteristic of the Maldive Archipelago.

We were able to observe a few changes in configuration of land and reefs in the 50 years since Gardiner's studies. Gardiner (1903: p. 399) reported Kuredu to be washing away to the south but extending to the north by the piling up of rock. At the time of our visit, the southern end appeared more extensive than shown on the chart, apparently due to added deposition of sand (Fig. 7). Gardiner (op. cit.) stated that many islands in Fadiffolu lagoon have washed away, a process that seems to be continuing. The reefs inside the channel between Kuredu and Fehingili Islands charted on Sheet No. 1, Admiralty Chart 66a, shown by Gardiner (1903: Fig. 103, p. 397), and mentioned in the Sailing Directions (U.S. Hydrographic Office Pub. 159, 1951), were not observed. Gardiner noted extensions of reefs from some islands into the channels. Such an extension was observed on the east side of Kuredu. This reef was charted neither on the 1835 Admiralty Chart nor by Gardiner. Gardiner mentioned a south island on Kuredu reef, which had been covered by coconut palms within the memory of people resident in 1899, but which then was "a mere sand bank with three small trees" (Gardiner, 1903: p. 399). There was no trace of this island in 1957 (Fig. 7).

During the stay at Fadiffolu, 'Argosy' was visited by several fishing dhonis, which are engaged in catching bonito. The fishermen wanted cigarettes and tin cans and traded shells for them. Shells used in trading, or given to members of the Expedition as gifts, included Cassis sp., Cypraea tigris, Conus aulicus, and Distorsio anus.

South Mahlosmadulu Atoll

Dunikolu (YSE Sta. 21)

'Argosy' sailed from Fadiffolu to the southwest corner of South Mahlosmadulu Atoll on 30 September, arriving at anchorage off Dunikolu I., on the rim of a faro in the lagoon, in the afternoon. From Dunikolu, a faro reef extends southward in the lagoon toward Varufinur and Furadu Islands (Fig. 8). Its highest point is about datum (MLWS). Many men were on the beach to meet us. One spoke a little English. They knew who we were and the names of our vessels, having learned from residents who had recently been to Male. A turtle nest with eggs was found. We loaned the Maldivians an extra face mask and they were delighted with it. Into the water they went, sarong and all! After our collecting, the Maldivians, mostly fisherman who live on Furadu, visited 'Argosy' and brought a large sack of turtle eggs and some coconuts.

It is a constant source of amazement to the newcomer to see a reef extending quite independently out across an atoll lagoon. The entire faro of which Dunikolu is a part was not investigated but has been discussed by Gardiner (1903). Along the velu side of the faro reef extending south from Dunikolu large specimens of Murex, Chama, Cypraea vitellus, and small Pustularia were collected among coral heads on the velu edge.

The narrow fringing reef on the southwest (velu) side of Dunikolu is sandy, followed by increasing numbers of living Acropora. Near the edge facing the main lagoon the reef is completely covered by low, living colonies of many coral species, and collecting is difficult as the depth is about datum. The edge slopes steeply into the lagoon; living coral covers the slope.

The reef opposite the east side of Dunikolu is similar but is separated by a lagoon ca. 50 m wide, the deepest part of which is ca. -5'. Toward the lagoon edge living coral increases in density to a ridge at the 0 - +0.5' level at the outer edge (Fig. 9). Most collecting here was done about halfway across the reef, where the substrate was of sand and rubble areas interspersed with large Acropora colonies and other coral heads. Specimens of several species of Cypraea occurred attached to the undersides of these colonies. Terebra spp. were found completely buried in sand amid rubble inshore.

No marine collecting or serious observations were carried out during the trip from North Male to Addu, 9-11 October, aboard 'Sea Quest'. In the lagoon of Mulaku Atoll, where we anchored in 14 m in a velu, a large number of small porpoises, which made very short, high jumps, were observed.

Addu Atoll

Upon arrival off Gan I., site of a Royal Air Force base, we were greeted and given much aid by extremely helpful RAF personnel. The commanding officer, Squadron Leader R. Schofield, graciously provided us with a motor tour of the island, space for a laboratory tent, meals, and inter-island transportation.

Hitadu (YSE Sta. 24)

This island, at the northwest extremity of the atoll, was visited 13 October in the company of British engineers seeking coral rock for landing strip construction. Holes due to a depth of about 7 m on Hitadu showed little but sand. There are many pieces of coral rock well inland on Hitadu, apparently thrown up by heavy seas. We collected on the seaward reef flat, which is 200-300 m wide and mainly of smooth, solid reef limestone pavement (Fig. 10) and resembles the seaward reef flat on the windward sides of the Marshall Islands (e.g., Emery, Tracey and Ladd, 1954: pl. 38). Loose dead coral rocks occur over much of the flat and many small living colonies of Heliopora occur almost to the beach. A channel is possibly developing along the edge of the beach. It was about 1 m wide with the bottom, a few inches below the lithified platform, of sand and dead coral rocks. At about 75% of the distance from shore to outer edge the amounts of living coral and, especially, coralline algae, increase markedly. In between, the platform is smooth and apparently scoured by the heavy surf. At the time of collection, breakers were usually about 5' high, and the depth of water over the reef was about 1'. The outer edge consisted of low, living coral and a broad but low "Lithothamnion" ridge, about 0.5-0.7' above the level of the main flat. In some areas, coral rocks covered with pink calcareous algae protrude a foot or more up into the heavy surf. In general, mollusks were not abundant. Cypraea moneta was collected under loose coral rocks. Bursa spp. were found inshore, but most of the other specimens collected were near the outer edge.

The large introduced terrestrial gastropod, Achatina fulica, was very common on Hitadu, although we had not seen it on any other atoll. Four specimens were collected on the central part of the island. Three of these showed symptoms of the disease reported by Mead (1961); both tentacles of two specimens, and one of the other, showed bulbous enlargements near the base or distally.

Gan (YSE Sta. 25)

A narrow reef on the lagoon (north) side of the island is about 80-100 m wide from high tide line to raised outer ridge. The outer ridge is composed solely of growing coral and is probably just exposed at spring lows. The reef face drops steeply to the floor of the lagoon. The inshore portion of the reef is characterized by large areas of silty sand, dead coral rocks, and abundant algae and appears to have had coral removed for runway construction. About halfway across, living coral begins and increases in density toward the outer edge. Many species of coral appear to be represented. Cerithium nodulosum was quite common.

Tridacna up to about 20 cm were common. It was not certain whether more than one species was present. Shell shape seemed largely determined by the nature of the coral in which the clam was embedded. No Tridacna were observed lying free on the sand.

YSE Sta. 25A. Reef area between the west side of Gan and Faidu. During World War II, a causeway joined the two islands. After the war it was destroyed by the Maldivians, whose two villages on either side, we were told, did not get along very well. Construction of the causeway unfortunately obscured the changes Gardiner (1903: p. 419) noted to have taken place between 1835 and 1900. However, an extremely strong current, flowing into the lagoon at the time of collection, is eroding the west side of Gan, as evidenced by fallen trees. The trunk of one coconut palm lay about 50 m out from shore under 2' of water. Gardiner (1903: p. 419) also observed evidence of erosion in this part of the atoll. The reef flat substrate was predominantly sand, with sparse coral heads and dead coral rocks, and some areas of dense living Porites colonies.

YSE Sta. 25B-C. Reef area on the lagoon side, near the east end of Gan. The width of the reef is about 80 m. Inshore portions consist of sand with areas of Thalassia(?) and dead coral rocks. The central area is of coral rubble, the outer portion of large living and dead corals. The gently sloping outer edge was densely populated with molluscs. Turbo sp. and Vasum turbinellum were especially common.

A turtle grass flat on the east end of Gan, adjacent to Gan Channel, was observed by two members of the crew, P. Melante and J. Blanchard, who collected more than 100 specimens of Cypraea tigris there.

Wiringili (YSE Sta. 26)

The broad lagoon reef, up to 800 m across, on the west side of Wiringili I. was visited 16 October. The substratum is mainly coarse sand, on which isolated coral heads and rather small Acropora colonies rest. Porites is the only abundant coral, but small, sparse colonies of several other corals were present. A transect of the reef from shore to outer edge was observed from the boat. The density of coral heads increases moderately from shore to outer edge. Clumps of coral heads at the outer edge form a ridge probably at about datum level. Behind the ridge is a lagoonlet about 4' deeper. The major (inshore) portion of the reef flat is at about the 0 to -1' level.

During the last six days at Addu (14-19 October) the weather was quite cool (daytime temperatures about 80° F) and rainy. Winds were light and variable. Rain squalls were large, moved slowly, and often blew back again after they once passed the island. Climatic conditions thus agreed with those reported by Agassiz (1903). They are due to Addu's location near the southern limit of the southwest and northeast monsoons, and north of the tradewind zone. Rainfall figures we were given ranged from 100 to 190". It is not unusual to have 2" in one day.

At Addu also, local boys often presented us with shells, e.g. Cypraea arabica. A shell appears to be a usual gift when a Maldivian greets a foreigner. Beyond the initial gift, the usual price for each shell is one cigarette. A number of cowries were added to the Expedition's collection in this way. At work in or outside our laboratory tent we were constantly surrounded by a number of Maldivians, chiefly children. They have picked up considerable English, and some of the men read English well.

The Expedition departed from the Maldives on 20 October 1957.

II. Peros Bahnos Atoll, Chagos Islands

The Yale Seychelles Expedition vessel 'Argosy' sailed south from Addu Atoll at 09:20 on 20 October 1957, gradually entering the region of the northwest monsoon, and entered the lagoon of Peros Banhos at 06:00 on 22 October. Although the northwest monsoon is said to be characterized by long periods of calm (Bourne, 1888), the weather was stormy, and seas were heavy in the broad, open lagoon, into which there are twelve large passages.

We went ashore only at Ile du Coin, the main settlement and headquarters of the well-kept copra plantation. We were informed that 7.05" of rain had fallen in the past 24 hours. Annual rainfall is 120-130".

It is of interest to compare our observations of the island with those of J. Stanley Gardiner and C. Forster Cooper (1907), who visited Ile du Coin in June, 1905. The main change in the past 50 years seemed to be that oil for export is no longer made from copra. In 1905, 65,000 gallons of oil were exported annually to Mauritius on three trips of a brig. Now, about 60 tons of copra are shipped each month on a small freighter to Mauritius, where the oil is pressed. Coconut oil is milled at Coin only for local consumption, although the very large old millstone used testifies to the formerly large production.

The human population of Peros Banhos is now 500, against 200 in 1905. Many of the people have lived all their lives in the Chagos, but although Gardiner and Cooper predicted that increase in numbers of these "enfants des îles" would eliminate the need to import laborers, many laborers continue to come from Mauritius. During the rainy periods of our visit, women were engaged in making coir rope. In good weather each woman splits 700 coconuts per day, a task requiring less than half a day, for 10 rupees per month, about the same wage paid in 1905.

Prominent cultivated trees are mapou (Pisonia), breadfruit, banana, and a few papayas. Flowers are grown, and the laborers have vegetable gardens. As was the case in 1905, pigs and chickens are kept for food and fed on coconuts. Ducks, not noted by Gardiner and Cooper, are now also raised. Donkeys were also present, but we saw no mules. The people and livestock appeared very healthy, a condition also remarked on by Gardiner and Cooper (1907).

Lagoon reef, Ile du Coin. (YSE Sta. 27)

The most conspicuous feature of the reef is the abundance of a single species of zoanthid which forms a broad inshore zone. Seaward of this is a zone of smooth reef limestone with a few low Porites heads and some zoanthids. The reef flat is at about 0 to -1' tide level (0 = MLWS). The seaward edge of the reef slopes rather gently. It is a region of heavy surge with few coral heads.

Molluscs collected included Cypraea caputserpentis, C. arabica (commonly in pairs on undersides of coral rocks, some with egg capsules); and members of the genera Cantharus, Mitra, Conus, Thais, Vasum, Amphiperas, and Tridacna.

Seaward Reef, Ile du Coin (YSE Sta. 28)

Collections were made on the broadest part of the reef, which is 250-300 m wide. Areas of fine sand, rough coral or reef rock, and smooth reef rock pavement characterize the inshore portion, which probably represents a region formerly occupied by the island. The proportion of smooth pavement increases, and it is covered by an algal mat of increasing thickness, to seaward. About 200 m from shore the substrate has a gently rolling appearance, and ranges in level from about -1.0' to +1.0'. Smoothed coral rocks typically occur in the depressions, and some rubble and occasionally sand is found underneath them. The number and size of such coral rocks increase toward the outer edge, where they are typically covered with pink coralline algae. The typical "Lithothamnion ridge" reported by Gardiner (1936) could not be visited because of the heavy surf. Although the tide was a low spring (+0.2' about two hours prior to our observation), the strong northwest wind had apparently prevented the reef from drying completely. Only portions of the outer ridge could be seen protruding through the surf. We were told by the plantation sub-manager that the reef often dries at low tide.

Just inshore from the Lithothamnion ridge the algal turf is 2-3 cm deep. Cup sponges (Phyllospongia foliascens) were extremely numerous on it. Conus was more abundant here than at any station visited in the Maldives; 135 specimens of 12 species were collected in 2½ hours. One specimen of Thais armigera (?) was observed feeding on Nerita plicata in the typical Nerita zone of inshore rock. In all, about 50 species of gastropods and 7 species of pelecypods were collected.

Gardiner (1936) concluded that the land of Peros Banhos was washing away, and that the atoll was progressing toward a submerged bank or drowned atoll, of which there are several in the Chagos Archipelago. We made no observations relevant to this hypothesis, except that the amount of dead reef and exposed reef rock observed was generally confirmatory.

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Table 1

Sea Surface Temperatures Over Maldive Coral Reefs, 1957

YSE Station	Location	Date	Time	Temp. (°C)
17	Funidu I., North Male Atoll (lagoon)	19 Sept.	17:15	29.5
		20 Sept.	10:45	28.7
23	Male I., North Male Atoll (channel)			
	near outer edge over coral	6 Oct.	11:00	28.9
	on inshore turtle grass flat		12:00	31.7
24	Hitadu I., Addu Atoll (seaward reef)	13 Oct.	10:00	29.5
25	Between Gan and Faidu Is., Addu Atoll	15 Oct.	10:30	29.5

Figure captions

Figure 1. Yale Seychelles Expedition vessel 'Argosy' off Addu Atoll.

Figure 2. View from Male Harbour approximately northeast to Funidu Island, North Male Atoll (YSE Sta. 17). The large island in the background is Hulule.

Figure 3. View south along outer edge of seaward reef of Hulule Island, North Male Atoll (YSE Sta. 22), showing coral heads apparently thrown up by waves.

Figure 4. View east across outer edge of seaward reef of Hulule Island, North Male Atoll (YSE Sta. 22).

Figure 5. View south along southern portion of seaward reef flat, Kuredu Island, Fadiffolu Atoll (YSE Sta. 20). The island and beach are to the left, the sandy, inshore portion of the reef in the center foreground, and coral increasing toward the outer edge, right background.

Figure 6. Large brackish water pond on the central portion of Kuredu Island, Fadiffolu Atoll.

Figure 7. View southwest from southern tip of Kuredu Island, toward Kudadu Island in distance, Fadiffolu Atoll. Seaward reef to right, lagoon to left.

Figure 8. View southwest from south shore of Dunikolu Island across faro reef (YSE Sta. 21) to Maruffinur Island in distance, South Mahlosmadulu Atoll. Velu to right, main lagoon to left.

Figure 9. View southeast across reef on east side of Dunikolu Island, South Mahlosmadulu Atoll (YSE Sta. 21). Beach in lower right corner, sandy inshore portion of reef in foreground, darker areas of coral and main lagoon beyond in background.

Figure 10. View northwest across seaward reef flat, Hitadu Island, Addu Atoll (YSE Sta. 24).


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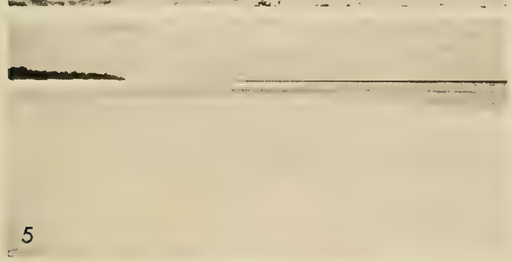
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ATOLL RESEARCH BULLETIN

No. 102

Notes on reef habitats and gastropod molluscs of a lagoon island at North Male Atoll, Maldives

by

Alan J. Kohn

Issued by

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Notes on reef habitats and gastropod molluscs of a lagoon island at North Male Atoll, Maldives

by

Alan J. Kohn [1]

North Male Atoll evinces most of the peculiarities characteristic of several Maldivian atolls but not found elsewhere. Its rim, with maximum dimensions of 51 x 37 km, is formed mainly by about 25 faros, small atolls within the larger complex. Also included in the rim are a few single islands partially surrounded by fringing reefs; the largest of these is Male Island, the seat of government. In addition, more than 80 faros and small islands occur within the lagoon. The faros and islands of the rim are separated by about 30 large channels around its entire circumference. The channels are 30 - 150 m deep, i.e. much deeper than typical Pacific atoll channels.

The large size of the channels results from meteorological and hydrographic conditions associated with the regular alternation of northeast and southwest monsoons. The resulting increased oceanic circulation in and through the lagoon is the proximate cause of the faros and inner or lagoon islands. The term composite atoll applies to North Male and some other Maldive atolls because of these features.

Origin of Maldive Atolls

Although I have held elsewhere (Kohn, 1961) that Darwin's subsidence theory is the best general explanation of the origin of atolls, other processes have probably been more important in determining the present features of the Maldive atolls. Certain aspects of Maldive atolls support the antecedent platform theory (Hoffmeister and Ladd, 1944).

Formation of Lagoon Islands

The islands within some Maldive atoll lagoons probably begin as coral growth on a platform at suitable depth (50-60 m). Growth is enhanced by the unusually large flow of oceanic water through the broad, deep channels, and conditions favor peripheral development of the reef into a faro (see Hoffmeister and Ladd, 1944). As the rim of the faro grows toward the surface, its integrity increases and its lagoon, known as the velu, becomes increasingly protected and a region of sediment deposition. Gradually, the faro is transformed into an island with a fringing reef. As Agassiz (1903) noted, all stages of such transformations may be observed on North Male Atoll.

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Funidu Island

The island studied is not named on charts, and we have transcribed the name given us orally by the inhabitants as Funidu. It is an elliptical island (about 138 x 89 m) just inside the main southeast channel into North Male lagoon and just northwest of a line between the northeast tip of Male Island and the south tip of Hulule Island. It is the unnamed island visited in 1901 or 1902 and described by Alexander Agassiz (1903: p. 43, pl. 9, fig. 2). Agassiz's description of the island is as follows:

> "As a type of an inner island, we examined a small well-wooded island which rises in the middle of the southeast passage into North Male with nearly thirty fathoms on either side on it. The island is elliptical, and is placed on the northwestern horn of an elliptical flat which stretches out in a southeasterly direction. The flat slopes very gently to the sea, is edged on the outer rim by a sink forming a shallow ditch of varying width, flanked by coral boulders or masses of beach rock extending as an irregular wall along the greater part of the outer edge of the reef flat. The greatest width of the reef is from two hundred and fifty to three hundred feet. It diminishes gradually in width to the northwestern corner, where the island is steep to. Corals grow in great abundance at a depth of from five to three fathoms upon the steep slopes of the reef flat; they grow with less profusion to six or seven fathoms, where they are separated by wide lanes and patches of sand which eventually cover the whole bottom at a depth of from eight to nine fathoms. From the three-fathom line, they also diminish in number towards the surface and spread over the edge of the flat, which is partly bare at low water; they extend but a short way over it, the greater part of the flat being covered by dead corals overgrown with Nullipores. The sand beaches surrounding the island are steep, from six to seven feet in height. The central part of the island is lower than the beaches which surround it, forming a shallow sink from twelve to eighteen inches or more in depth. Considerable moisture accumulates in this shallow sink, and in the rainy season a pool is probably formed of more or less brackish water. This structure is most characteristic of the islands of the Maldives, whether they occur in the interior of the great sheets of enclosed waters or on the outer rims of the plateaus. The sink has been formed by the washing up of the beaches round a central area, as we have seen it in the Paumotus and elsewhere in other Pacific atolls. Before the vegetation became too dense, beach sand was blown towards the interior and partly filled the central area, until this was prevented by the growth of bushes and shrubs, when the beaches merely increased in height and the sand of the upper ridge of the beach was driven sparingly

towards the centre of the island, or its further passage stopped by the belt of denser vegetation which had come up on the higher parts of the coral sand beach. The island of Male has gradually developed and been formed much in the same manner as this island."

The account describes the island much as we observed it in 1957, except we do not recall that the central portion appeared lower than the uppermost beaches. Perhaps during the intervening 55 years sufficient sand has blown onto the island to eliminate the vestiges of the velu, as apparently happened earlier on Male.

Agassiz's observations of the fringing reef around Funidu are confined to the following note on the corals:

"The corals growing on the slopes of this island are marked for their luxuriance; they grow as abundantly as they do on the sea face of any atoll. This is in striking contrast to their scanty development in the interior of typical lagoons. It can readily be explained from the great depths of the passes and the great mass and purity of the water passing into the interior of the enclosed basin of North Male. . . The branching corals consist mainly of species of Madrepores, of Pocillopores, and Millepores. While the massive corals are usually Astreans, Porites, and the like, Maeandrinae are not common."

With Dr. Willard D. Hartman, I made four trips to Funidu Island, 19-23 September 1957, during the course of the Yale Seychelles Expedition. Notes on habitats and inhabitants were referred approximately to the coordinates indicated in fig. 1, as accurately as could be done in the field (see Kohn, 1956, for method of recording data). The density of symbols in fig. 1 indicates the relative thoroughness of the observations. The gastropod molluscs have been identified from collections of the Peabody Museum of Natural History, Yale University. No attempt has been made to verify further the names used.

On the north side of the island (quadrats B4-B8) the sand beach is narrow and followed seaward by about 12 m of sloping beachrock covered with a thin algal mat, in the intertidal zone. The surface of the beachrock is smooth, but it is marked by depressions, potholes, and crevices. Seaward of this zone at about the tidal datum (0: approximately mean low water springs), the beachrock becomes a very smooth level bench covered with a thin layer of sand. The width of this zone is mainly 7 m or less. Seaward is a wide zone of living corals in very shallow water, the tops of the heads appearing to extend above datum. Mitra litterata Lamarck and other species of Mitra were collected in shallow crevices in the limestone and Trochus flammulatus Lamarck on live coral in the outer zone as well as on inshore beach rock at about 0 - +1' tide level. In B8, some rocks (nature not recorded) extended upward to about +2' and perhaps suggest rather recent elevation.

On the east side of the island, a large tide pool is in C9. The following were collected in C9 and D9 on beach rock exposed at low tide: Thais tuberosa Röding, Nerita histrio L., Engina mendicaria L., Vasum turbinellum L., and Bursa sp.

Quadrats F5-F8 are characterized by a flat, smooth limestone pavement covered by a very thin layer of sand immediately seaward of the rather steep, coarse sand beach. Latirus smaragdula (L.) was ubiquitous on this thin layer of sand. Drupa spp., Morula spp., Peristernia sp., Nassarius sp., and Columbella sp., were also present. Mitra spp. were collected from crevices in the limestone rock. Seaward, the sand-covered bench supports isolated coral heads. The sandy area is gradually reduced and the coral becomes increasingly dense and solid toward the outer edge (G5, G6, H4, H5, H6).

In F7, smooth beachrock slopes offshore at about a 30° angle just offshore from the narrow sand beach. In some areas there are two tiers of beachrock. Latirus smaragdula and Mitra litterata were collected on this beachrock. Offshore portions of the reef on the east side could not be investigated because of the rather heavy surf. There appeared to be much coral rubble and dead coral in this region. Increased abundance of Drupa morum Röding was noted in F7 and is probably correlated with the heavier surf in this region. Morula tuberculata Blainville, not found in calmer areas to the west, was also present. It occurred both intertidally and subtidally; other species collected in this quadrat appeared to be only subtidal. The substratum of F8 is mainly beachrock and closely resembles F7.

A broader sand beach is present on the west side (C3, D3), followed seaward by a broad area of thin sand on smooth, level limestone bench which forms a channel suitable for landing a small boat in C3. Specimens of Turbo argyrostoma L., with epizoic Hipponix sp., Vasum turbinellum, Nassarius graniferus (Kiener), Cerithium sp., Strombus mutabilis Swainson, Polinices sp., Mitra mitra L., Drupa grossularia lobata Blainville, and Peristernia nassatula Lamarck were collected in this area. Seaward (C2, D2, E2) is a zone of dense growing coral. The heads appear to extend several inches above datum, and many species of coral are present. The heads are interspersed with sandy areas containing some rubble, the substrate being at about -2.5'. In some places there is a very gentle slope to the reef edge, which drops off precipitously into blue water (about 90 m acc. Admiralty Chart 6[illegible]). Turbo argyrostoma were collected from living coral, their shells often bearing epizoic Hipponix sp. Lambis lambis (L.) occurred on sand under overhanging coral heads, and Atrina sp. occurred buried in sand. Cerithium nodulosum, Cerithium sp., Peristernia nassatula occurred on sand amid living and dead coral; Drupa ricinus (L.), D. grossularia lobata, and Latirus smaragdula on dead coral; and Morula elata Blainville, Thais hystrix L., and Cypraea sp. cf. C. poraria L. on living coral heads. Mitra litterata, Mitra sp., Vasum turbinellum, and a haliotid also occurred in C2, D2, and E2.

Unidentified species of Nassarius and Mitra were collected completely buried in sand under coral rocks in unidentified quadrats.

Conus at *Funidu*. I am presently preparing a more detailed report on *Conus* in the Maldives, to be published elsewhere, and will therefore only briefly summarize the occurrence of this genus at Funidu. In all, 199 specimens of 16 species of *Conus* were collected. *Conus* was most abundant on beachrock, where average density was about one individual per square meter.

Acknowledgment

The Yale Seychelles Expedition, during which these observations were made, was made possible by the generosity of Mr. Alfred C. Glassell, Jr.

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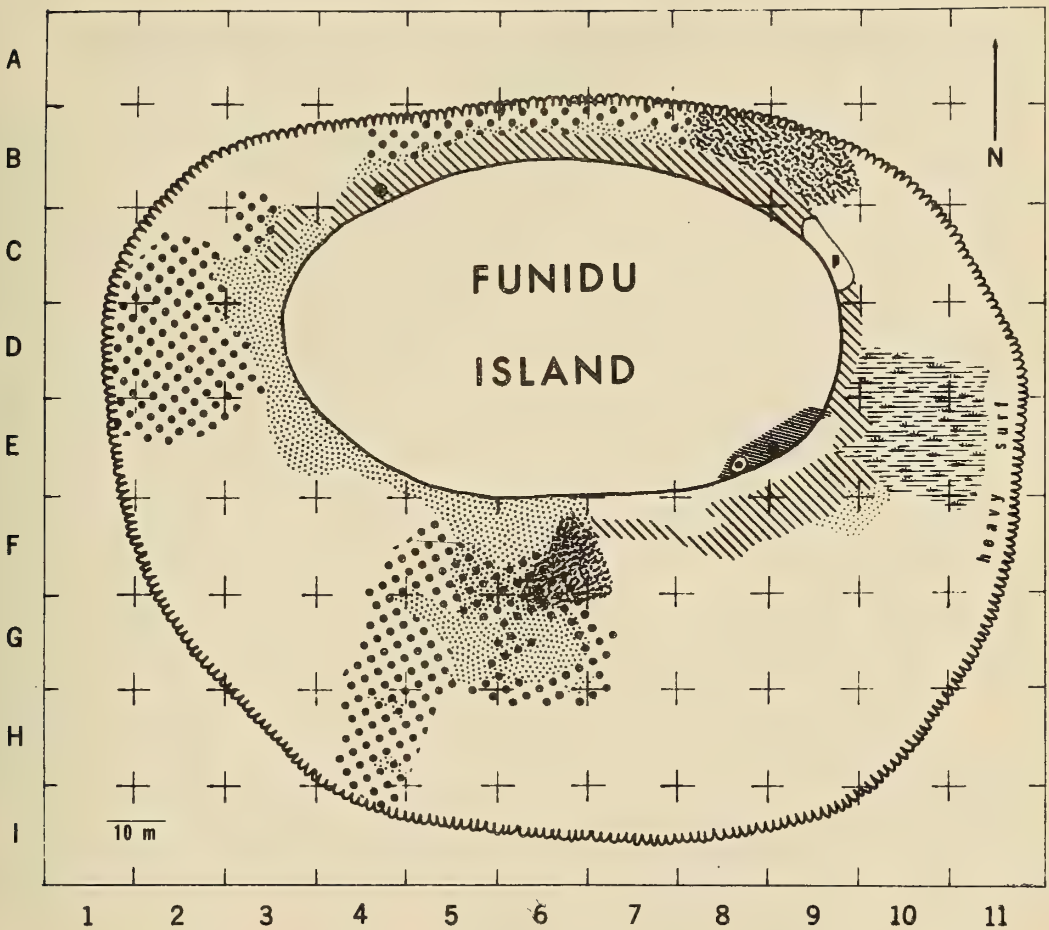
Caption for map on following page:

Funidu Island and fringing reef, North Male Atoll, Maldive Islands ($4^\circ 10'$ N, $73^\circ 25'$ E). The substratum of portions of the reef flat examined, and other features, are indicated by symbols. Based on H.O. Chart 5664 and observations by the author, 19-23 September 1957.



smooth, sloping beachrock with thin layer of algae

flat, smooth limestone pavement with very thin layer of sand

living coral heads

dead coral heads and rubble

coral rubble

apparently eroding portion of island

tide pool

tree stump

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Observations on the birds of French Frigate Shoal and Kure Atoll

by

Miklos D. F. Udvardy and Richard E. Warner

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Observations on the birds of French Frigate Shoal and Kure Atoll

by

Miklos D. F. Udvardy [1/] and Richard E. Warner [2/]

Through the courtesy of the United States Coast Guard the authors spent an hour on September 2, 1961 on Tern Island, French Frigate Shoal, and visited Kure Atoll from September 12 to 14, 1961, during the Harold J. Coolidge Expedition to the atolls of the Northwest Hawaiian Chain (Udvardy 1961)[3/]. Both places have undergone drastic changes during the last few years and however few our observations are, their documentation should contribute to future studies of the islands.

French Frigate Shoal

Tern Island of French Frigate Shoal has been converted to an airstrip, and sparse vegetation grows only on a margin of about 50 meters width on the north and south sides of the airstrip, on loose and partially bare coral sand (Svihla, 1957; Lamoureux, 1961).

No sign of any bird nesting activities was found on Tern Island. Twelve Golden Plovers (Pluvialis dominica ssp.), 29 Ruddy Turnstones (Arenaria i. interpres (Linn.)) and 1 Sanderling (Crocethia alba (Pall.)) were the only transient or wintering residents of the island, the plovers running on the airstrip, the others on the margin of the island (the airstrip embankment is mostly supported by corrugated iron breakwaters). Only three individuals of sea birds were in the air around Tern Island, i.e., a Sooty Tern (Sterna fuscata Bloxam), a Fairy Tern (Gygis alba (Gm.)) and a juvenile Red-footed Booby (Sula sula rubripes Gould).

It is worth mentioning that a disintegrating carcass of a hatchling green sea turtle (Chelonia mydas (L.)) was picked up by one of us on the north margin of the airstrip, in loose coral sand, with the carapace crushed.

Kure Atoll

The vegetation and the bird fauna of Kure Atoll have been described by Kenyon and Rice (1958) as late as 1957. Green Island was then approximately 1½ miles long, and 1 mile wide, with 10 to 20 foot-high dunes behind the beach. It was almost wholly covered with an "almost impenetrable" thicket of Scaevola bushes, except one interior opening of low herbaceous vegetation.

1/ University of British Columbia, Vancouver, Canada.

2/ Museum of Vertebrate Zoology, Berkeley, California.

3/ A grant of the National Research Council of Canada, partly used on this expedition, is gratefully acknowledged.

In December, 1959, Dr. Chandler Robbins, Jr. informed one of us (pers. communication to M.D.F. Udvardy) that he had just visited Kure Atoll, and that a project had been started there by the U. S. Navy to "improve" Kure for the nesting of the two albatross species. The scheme was an attempt to compensate for the population losses on the Midway islands. Zig-zag strips (cf. Figs. 2 and 4) were plowed bare of the Scaevola bushes so that these birds could find more take-off and nesting possibilities.

Little trace of these changes could be detected on Green Island in September, 1961; for still greater changes have since drastically altered the vegetation. Early in 1961 an U.S. Coast Guard "Loran" station was established there.

An estimated one third of the island—its whole narrower end—is taken up by an airfield. The airfield (Figs. 1, 2) is bordered by Scaevola of 2-3 meters height and some Messerschmidia trees. Part of the southern half of the remainder consists of houses, roads, playfield and lawns. In the west center of the island there is a 625 foot high antenna. Its system of guy-wires reaches almost to the beach on the North side, and covers the central flat and open part of the remainder of the island (Figs. 3, 4). The land under these wires is cleared. Coherent, undisturbed vegetation occurs on the beach crest of the southwest, west and northwest side of the island, and a Scaevola strip around the rest of it. The west side of the interior of the island, where not plowed, consists of low Scaevola and patches of Boerhavia, or Eragrostis bunchgrass, with one extensive grassy area (presumably the "interior opening of low herbaceous vegetation" of Kenyon and Rice l.c.). The flora of the island is described by Lamoureux (1961) of the same expedition; Clay (1961) shows two photographs of the island.

As bird habitat, the runway and the settlement are naturally excluded. The interior had numerous nesting pairs of Masked Boobies (Sula dactylatra Gould) and Red-tailed Tropic-Birds (Phaethon rubricauda (Mathews)), both species with young ranging from downy nestlings to almost fledged young. The interior, and even the previously cleared area, now largely vegetated with Boerhavia, had numerous (i.e., many hundreds, but no estimate was attempted) burrows inhabited by Wedge-tailed Shearwaters (Puffinus pacificus Lesson), and by the Bonin Island Petrels (Pterodroma hypoleuca Salvin) that did not yet start to nest but visited the island every evening. The Scaevola thicket of the beach crest had nesting Red-tailed Tropic-Birds, Great Frigate Birds (Fregata minor Gmelin) and Red-footed Boobies, the latter especially on the taller trees of the southeastern dunes of the island.

A dozen or so Bristle-thighed Curlews (Numenius tahitiensis Gmelin) were seen in loose groups on the beach, together with about 35-40 Ruddy Turnstones, and 8-10 Wandering Tattlers (Heteroscelus incanum (Gmelin)). More curlews fed on the open and low grassy areas of the island interior, where turnstones only rarely were flushed. Fourteen Golden Plovers mostly kept to the runway and the open sand pit at the east end of the island. On the northeast of the island 20-30 "Hawaiian Terns" (White-capped Noddy, Anous tenuirostris Guy) were on Scaevola bushes.

On September 12, we visited the larger of the two sand bars which are, besides Green Island, the only visible parts of the atoll. On this 400 meter-long sand bar, practically devoid of vegetation, only a dozen Bristle-thighed Curlews and a number of Noddy Terns (Anous stolidus (Scop.)), common also on Tern Island's beach line, were seen.

We found 40 Hawaiian Monk Seals (Monachus schauinslandi Matschie) on this sand bar. The north and northeastern side of Tern Island seemed to be a favorite howling ground of the seals, and 25-30 seals were counted there on the early afternoon of September 12 and 13. The seals slept on the beach crest, in the shadow of the tall Scaevola bushes.

Several of us systematically searched for dead, or injured birds under the guy wires. In a short time the following were found:

Frigate birds	2
Red-tailed Tropic-Birds	2
Sooty Tern	1
Gray-backed Tern (Sterna lunata Peale)	1
Wedge-tailed Shearwaters	2

During our stay we witnessed several such accidents. The tropic-birds are apt to hit the wires during their mid-day aerial displays, and the frigate birds during their communal soarings. The shearwaters and petrels seem to hit the wires at night, partially blinded by the electric lights on the buildings.

As a conclusion of our observations, Kure is no place for the soaring albatrosses now, except perhaps the beach, which could harbour a few black-footed albatross pairs. The guy-wires will in all likelihood very effectively keep them off. The other sea birds may stay, if no further habitat is altered, in the way they had lived on the Midway islands, with the extra toll taken on their populations by the hazards of living near and on human habitations.

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Legends to figures

Figure 1. Loran station living facilities, fuel oil tanks, and runway, looking SSW. The heavy, uninterrupted Scaevola thicket which occupies the right center, is nesting ground of frigate birds, masked boobies and red-tailed tropic-birds. The hollow beach line to the left of the runway is the favorite hawling ground of monk seals. Green Island, Kure Atoll, September 1961.

Figure 2. Portion of airstrip, Green Island, Kure Atoll. Note Loran tower guy wires and radial bulldozer paths. Zig-zag strips of sand, on top and left center, are the result of 1959 bulldozing operations to create albatross runways. September 1961.

Figure 3. Vertical view from top of Loran tower, SE side, height 625 feet. Note changes in vegetation due to activities. Green Island, Kure Atoll, September 1961.

Figure 4. SE view of vegetation changes from Loran tower. Height 625 feet. Note guy wires and narrow, recent bulldozer paths. Strip bulldozed in 1959 shown from top to bottom center. Curlews use it for feeding together with the grassy patches shown in lower half of picture. Wedge-tailed shearwaters and Bonin Island Petrels also burrow on the wide strip. Green Island, Kure Atoll, September 1961.

All photos courtesy Foundation of Environmental Biology.

Figure 1

Figure 2

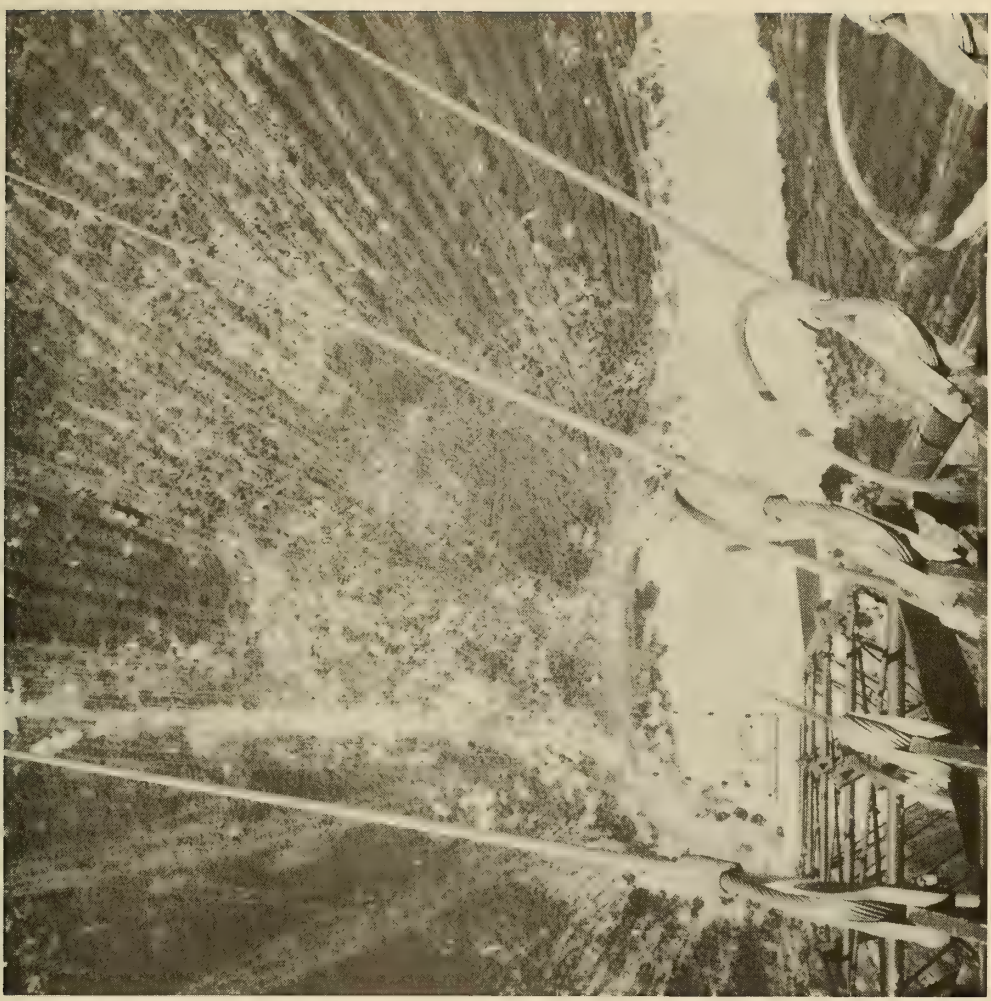

Figure 3

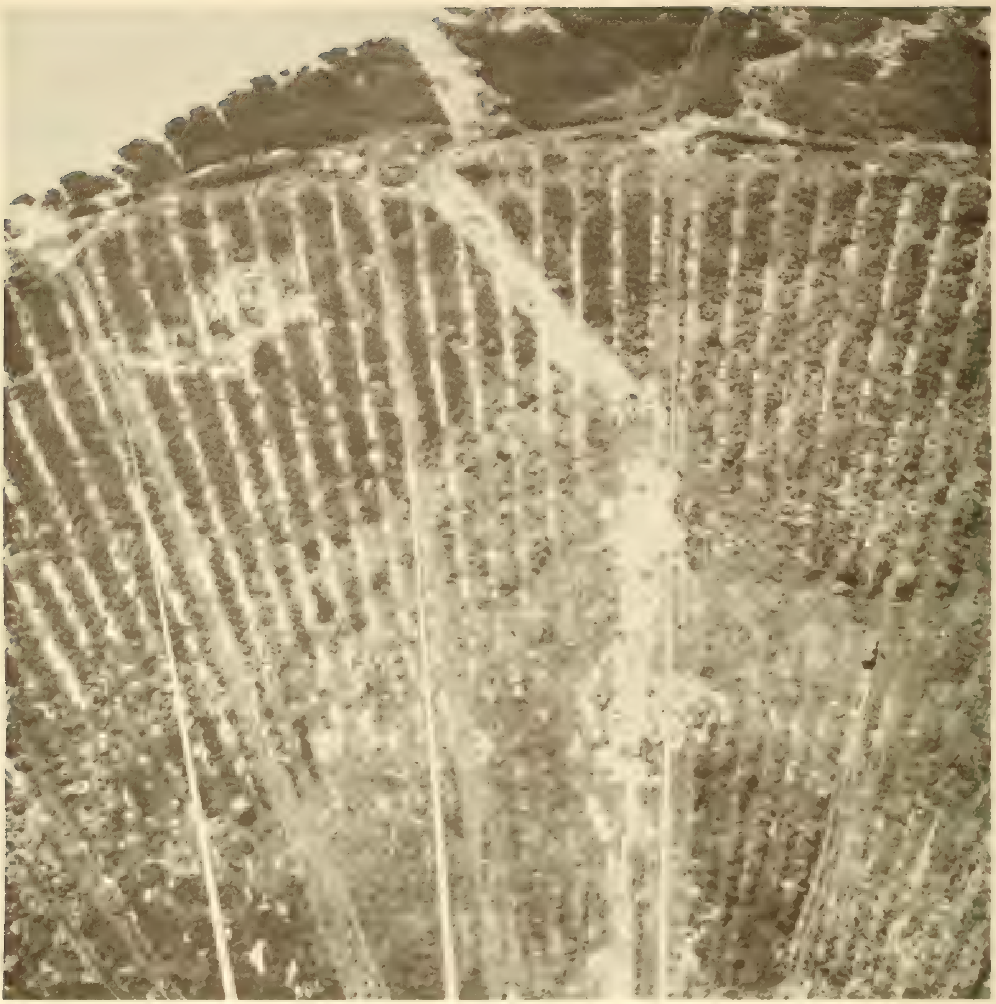

Figure 4

ATOLL RESEARCH BULLETIN

No. 104

Carbonate sediments of Half Moon Cay, British Honduras

by

D. R. Stoddart

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Carbonate sediments of Half Moon Cay, British Honduras

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The reef islands of the British Honduras barrier reef and atolls have been the subject of a series of reports (Stoddart 1962, 1963), to which the present paper is essentially supplementary. Earlier papers were concerned with the distribution and areal variation of the reef islands, about which little was previously known. Mapping of topography, sediment distribution, and gross vegetation patterns involved the approximate delimitation of "ecologic field units" (Cloud 1952) for use in constructing field maps. As in other reef studies, a primary distinction was made in sediment distribution between fine ("sand") and coarse ("shingle") sediments, which with qualifying adjectives ("fine", "medium", "coarse") became the basis of sediment mapping.

The data reported here result from an attempt to define the limits of these sediment units in quantitative terms, and the results are of interest primarily in terms of the original field reports. They are not intended as a contribution to the study of carbonate sediments as such. Because of the limited time available no specific sampling design was set up, and samples were simply collected along the course of levelling traverses. Generally these were oriented normal to the beach, and hence parallel to the greatest sediment gradients. The great variability in sediment pattern on most foreshore areas presents a major problem, which in any subsequent design would require stratified random sampling (Krumbein 1954, Krumbein and Slack 1956). The density of sampling points also varied inversely with vegetation cover: at Half Moon Cay few samples were taken from the dense Cordia-Bursera bush at the west end of the island. Because of this variability and the absence of design, no attempt is made to draw any conclusions from these data on, for example, the relative importance of contributing organisms in above-water sediments. The aim is to demonstrate the quantitative significance of the terms "sand" and "shingle" as applied to British Honduras cays, and to explore the relationship between sediment calibre and organic constituents in the collected samples.

When this work was in progress, few papers had been published on reef-island sediments, with the notable exception of the Bikini reports (Emery, Tracey and Ladd 1954, pp. 35-43). Tracey, Abbott and Arnow (1961, pp. 58-67) have reported on the sediments of Ifaluk Atoll. The paucity of the literature is in strong contrast to that on underwater carbonate sediments. A major advance in the study of above-water carbonate sediments has resulted from the work of Robert L. Folk and associates in the southern Gulf of Mexico. Folk, Hayes and Shoji (1962) have described carbonate sediments from Isla Mujeres, east coast of Yucatan; Charles Hoskin (1963) has included beach sediments in his comprehensive study of Alacran Reef sediments; and Folk himself (1962) has treated the relations of size and sorting in carbonate beach sediments at several Gulf of Mexico beach locations. The fundamental study

of Caribbean reef island sediments is that of Folk and Robles (1964) on the sediments of Isla Perez, Alacran Reef; Professor Folk kindly allowed me to read the manuscript of this paper while in the field in 1961 and some of the data reported here supplement his conclusions. Folk and his associates are working on further studies of other Alacran island sediments.

Procedure

Most of the samples described were collected in 1961 by the writer and Stephen P. Murray at Half Moon Cay, Lighthouse Reef. Half Moon Cay lies on the eastern (windward) reef flat of the Lighthouse Reef atoll, at a point where the reef front curves sharply westwards (Figure 1). Tidal range is small, and the dominant waves are easterly and north-easterly, refracting round the reef angle to approach the south side of the island from the southeast. The island itself is 1100 yards long. It is highest along the south and southeast shores, where in 1961 it reached a maximum height of 10 feet above sea level. The island falls naturally into two parts. The eastern sector, built of sand except for shingle ridges at the eastern point, is arcuate in shape, with a steep ridge 10 feet high facing the southeast bay, the surface falling quite steeply to the northern shore. This part of the cay is covered with coconuts, with little ground vegetation. The western sector of the cay is still covered with a dense thicket of vegetation, mainly Cordia sebestena and Bursera simaruba. The south shore is formed by a shingle ridge, decreasing in height (in 1961) from [illegible] feet at the east end to 3 feet at the west. The cay surface falls gently from this ridge crest towards the north shore, and is built of sand and rotten coral fragments. The north shore is sandy and subject to wave action only during winter "northers"; the offshore area is covered with Thalassia, with only a few scattered coral patches. Off the south shores, steep waves enter the southeast bay, which is floored with strongly rippled sand with little living reef. Further west, off the south shingle shore, living reef approaches within a few feet of the shore itself. Cemented beach sands are widespread in the intertidal area, but are not treated in this paper; for a full account of the island, with contoured topographic maps, see Stoddart 1962, pp. 64-77, Figures 30-34, and Stoddart 1963, pp. 94-98, Figures 58-61.

In addition to the Half Moon Cay samples, samples were also taken from shoal water areas (less than 2 fathoms) on the atolls and barrier reefs, and in the Turneffe lagoon, and from a number of other islands, chiefly Rendezvous Cay and Cay Glory (barrier reef), Northern Cay (Lighthouse Reef), Southwest Cays (Glover's Reef), some of the central barrier reef lagoon cays, and a few mainland and barrier beach stations. All the sediments consisted of carbonates, except for quartz sands from the mainland and barrier beach stations. The samples taken in 1961 at Rendezvous and Half Moon Cays were repeated as far as possible in 1962, following major changes to cay sediments and topography during Hurricane Hattie in October 1961. In all 202 samples were studied, of which 155 are from Half Moon Cay.

Different techniques were necessarily adopted for sand and shingle size material. For sand size sediments, surface scoop samples of approximately 750 grams were collected, and taken to Cambridge for sieving with a nest of British Standard sieves, and for microscopic inspection to determine approximate organic constitution. Approximate organic constitution was noted during this inspection, but no more refined analysis was carried out. Cumulative frequency curves were constructed from the sieving data, and mean size and sorting values computed, using the methods recommended by McCammon (1962):

$$\text{Ø Mean size} = \frac{Ø16 + Ø50 + Ø84}{3}$$

$$\text{Ø Sorting} = \frac{Ø85 + Ø95 - Ø5 - Ø15}{5.4}$$

Size values are given in phi (Ø) units ($Ø = -\log_2 D$, where D is particle diameter in millimeters) for ease of handling (Krumbein and Pettijohn 1938, p. 84). Zero Ø is equivalent to a particle size of 1 mm; smaller particle sizes are indicated by positive and larger by negative Ø values. Ø percentiles were read from the cumulative curves.

Only sand size sediments and small shingle up to -6Ø could be taken to Cambridge; larger shingle and boulder size sediments evade standardised sieving treatment. For coarse sediments, the technique adopted was to measure the long axis of not less than 50 particles in the field, to construct cumulative frequency curves from this data, and to calculate mean size and sorting values. Since the cumulative frequency curves of sand samples express the quantity of sand by weight in each class interval rather than the number of particles retained by each sieve, it was decided in the case of measured long axes to sum the lengths of particles within each class interval rather than the numbers of particles, as do Folk and Robles for Isla Perez shingle. Folk and Robles constructed frequency curves by numbers, and converted these to weight frequency distributions by adding approximately 0.5Ø to the number value (Folk 1962, p. 232). In this case Folk was dealing mainly with Acropora cervicornis shingle, in which particle volume and shape bear some stable relationship to long axis measurement. Different relationships obtain, however, when dealing with other organisms, such as globular or hemispherical corals. For this reason the sums of lengths method is used, since it is probably more directly comparable over the whole shingle range to the weight measurements of sands. This technique for handling coarse material is extremely unsophisticated: its chief merits are speed and ease of execution under conditions of discomfort. Owing to the inherent qualities of reef-derived organic carbonate material, there is usually no question of deriving simple shape parameters such as those of Zingg (1935) or Sneed and Folk (1958), using three-dimensional and other measurements. The problem of the quantitative description of highly irregular particles such as reef-derived sediments has yet to be investigated in detail, and is not dealt with here.

Size Characteristics and Origin

The dominant characteristic of reef island sediments, taken as a single population, is bimodality. Figure 2 includes cumulative frequency curves for 115 samples from Half Moon Cay, collected in 1961. The samples divide themselves quite clearly into two families: one with a mean size ranging from about -0.[illegible]Ø to +1.[illegible]Ø, fairly tightly grouped; the other, with a rather wider range, from about -5 to -10Ø, but strongly clustered round -[illegible]Ø. These correspond, respectively, with the "sand" and "shingle and boulders" of the cay descriptions. There is no apparent gradation in size between the two. Some sand samples contain larger shingle fragments, accounting for the open ended curves on the right of Figure 2, but the distinction between the two families is otherwise abrupt. To an undetermined extent this distinction may be due to the two methods of measuring sediments used, but this is unlikely to be very significant. The curves show that sediments larger than -10Ø, between -5 and -1Ø, and finer than +2Ø are uncommon on sand and shingle cays. Fine sediments are probably important on mangrove islands, but no samples were taken. This sharp distinction between two types of sediment is primary evidence of (a) the diverse origin of cay sediments, and (b) the particular breakdown patterns of sediments of organic origin on cays. At the same time, the distinction hides other finer variations within each of the major sediment families, variations which, though expressed topographically and in sediment calibre, can be understood only by reference to the organisms from which the sediments derive. In this, cay sediments differ fundamentally from most beach materials, such as the Placencia quartz sands on the mainland coast.

Composition

Cay sediments are derived from the wide and complex range of organisms of many shapes and sizes forming and inhabiting the living reef and near-reef environments, and subject to sorting and modification by marine action. Theoretically, the size and shape of sediment particles on cays may be initially as varied as those of any reef organism, within the range of the transporting capacity of the waves. Attrition by waves, subaerial weathering, or biological means may produce further changes in both size and shape, the products of which may be selectively transported and deposited by waves and currents. While generalization is, therefore, difficult, it is soon recognized in the field that sediments of certain sizes tend to consist largely or even exclusively of single organisms. Thus boulder material (larger than -9Ø) consists of whole hemispherical coral colonies, often deposited by storm waves beyond the reach of normal wave action and exposed to chemical weathering only; intermediate shingle (-[illegible]Ø) consists of fragmented Acropora colonies, smaller corals and shells; coarse sand (0Ø) of algal fragments; and medium sand (+0.5Ø) of fragmented coral particles and colonial foraminifera.

In most of these cases, the characteristics of the sediment reflect directly the characteristics of the dominant constituent organism. Since each organism usually has fairly sharply defined size and shape characteristics, sediments which consist largely of a single organism have similar size and shape characteristics. Thus reef-flat colonies of Siderastrea and Diploria, growing to diameters of 2-3 feet, when piled up by waves form a sediment in the size range -9 to -10Ø, with rounded and hemispherical particles. Acropora cervicornis, which when growing forms tangled thickets with narrow cylindrical stems and branches, may be broken down by waves into cylindrical fragments up to -7Ø (5 inches) long and -3.5 to -4.5Ø diameter, closely following the original growth dimensions. Halimeda is a bushy green alga with abundant plate-like segments up to 8 mm (-3Ø) in diameter, but extremely thin; when the segments are detached by wave action and accumulate they form a sediment with a mean size of 0 to -2Ø. These groups of organisms are among the most abundant; other organisms also have characteristic shapes and sizes, but are not usually present in sufficient quantity to dominate the characteristics of a sediment population.

Constituent organic materials control not only the size characteristics of a sediment, but also the sorting, or measure of the spread of grain sizes present. In sediments derived from a single organic constituent, the mean size will closely reflect the size of the original organism, and the sorting will reflect the range of sizes present in the living population. In general, sizes of living reef organisms tend to cluster fairly tightly round a mean value, and the derived sediment shows small scatter about the mean size, or is well sorted. This applies to most sediments composed of a single type of organic constituent. Selective transportation by waves imposes a secondary sorting effect, but this is apparently less important than the primary composition of the sediment. When a sediment is composed of more than one organic constituent, each will influence the sediment characteristics in proportion to its abundance. Hence samples composed of coral grit and Halimeda, or Acropora sticks and smaller corals, will have a bimodal frequency distribution, with poorer sorting as the dominance of a single organism decreases. In some samples, particularly underwater samples, as on the Turneffe lagoon floor, many organisms are present and the sorting is extremely poor. On cays, however, most sediments are formed from one or two main constituents, are moderately or well sorted, and closely reflect the size and shape of the original contributing organisms.

In British Honduras, the main sediment sources and sediment-contributing organisms, in order of decreasing size, are as follows:

1. Conglomerate beachrock blocks, dislodged from beachrock pavements by wave action. Except for some massive corals these form the largest particles, up to -10Ø in longest dimension. Their shape is plate-like, and probably because fracture is conditioned by inherent joint weaknesses in the beachrock, the fragments tend to be of closely similar size: the sediment is thus extremely well sorted.

2. Large hemispheric corals of the genera Montastrea, Diploria, Siderastrea, etc. These vary from -8 to -10Ø, but the larger specimens are very rare.

3. Acropora palmata: a massive branched coral (elkhorn), in which the branches break down into slabs which exceptionally are up to -9Ø (20 inches) long, but are more usually -7 to -8Ø (5-10 inches) in length and up to 2 inches thick. This is more widespread in rough water areas, particularly as a shingle ridge constituent on the atoll islands.

4. Gastropod shells, particularly massive specimens of Strombus gigas, which are locally very abundant. They are generally found whole, with greatest dimensions of about -7Ø, but may break down under severe wave action into curved and disc-shaped fragments.

5. Acropora cervicornis, one of the most important sediment producers and perhaps the most widespread constituent of shingle ridges. Dimensions of the original colony vary considerably with depth and degree of exposure to wave action. In exposed locations the branches are stubby, massive and tightly clustered; in calm water the colonies are open-branched and taller. The diameter of branches is normally greater in deeper and rougher water, and is least in protected barrier reef areas. For data on growth form at Alacran, see Kornicker and Boyd 1962, pp. 667-668. In most shingle ridges A. cervicornis branches vary from -5 to -7Ø in length, but on protected barrier reef cays such as Robinson Point and Wild Cane Cay they rarely exceed -5Ø.

6. Medium hemispheric corals, a group which includes such small corals as Siderastrea radians, Dichocoenia, Isophyllastrea, Porites astreoides, small Montastrea, etc., varying in size from -6. [illegible] to -[illegible]. These colonies are generally mixed with Acropora fragments in shingle ridges.

7. Small corals such as Porites, Favia and Siderastrea, in the size range -5 to -6Ø: these are not individually important sediment sources.

8. Nodular algae, particularly Goniolithon boergesenii. Goniolithon forms loose nodules, cylindrical in shape with a smooth or mamillate surface, up to -[illegible].5Ø in length. Goniolithon is found living on the east reefs of Lighthouse and Glover's Reef cays, where it forms a prominent minor constituent of shingle ridges. It is possible that fragmented Goniolithon is important in the sand fraction, where it has not yet been identified.

9. Branching algae, including the massively branched Goniolithon strictum and the more delicate Lithothamnion [illegible]careum. These are found in all reef provinces, but are quantitatively unimportant as sediment sources.

10. Halimeda fronds, which are the main constituent of coarse sands. The segments are easily distinguished by their shape and dead white, chalky appearance. They are mainly retained by the Nos. 5 and 10 sieves, have a maximum diameter of about -2Ø, and form sediments with median diameter approximately 0Ø. Individual segments break into two or three fragments which are easily identified by shape and structure. In the Pacific Halimeda is more important as a source of lagoon floor sediments than as a beach constituent (see, for example, Tracey, Abbott and Arnow 1961, p. 65).

11. Coral grit, fragments of corals no longer identifiable, consisting of equant, greyish particles, highly polished in areas of high wave action but dull on protected beaches, and invariably mixed with small amounts of red Homotrema as a secondary constituent. Coral grit is largely retained by the Nos. 22 and 30 sieves, with mean sizes of 0.5 to +1Ø, extending down to +2Ø. Coral grit is the dominant constituent of medium and fine sands.

12. Small organic debris found in most sand samples, but individually and collectively of small importance. The group includes echinoderm spines and tests, peneroplid foraminifera, gastropod and pelecypod tests, sponge spicules and fish bones. Foraminifera as a group are not important in cay sands, by contrast to most Pacific atolls.

13. Very fine sediments, +2Ø and finer, of unidentified origin and quantitatively insignificant, found in many samples of fine sand.

14. Finally, the remains of many other reef-dwelling organisms which are thrown up on beaches and contribute in some way to cay sediments. These include the remains of numerous gorgonians, sponges and crustaceans.

Breakdown

Field observation and sediment samples show that of these groups, three are dominant in the formation of cay sediments:

1. Acropora cervicornis sticks and similar size corals in the shingle class;

2. Halimeda segments in the coarse sand class; and

3. Coral grit with Homotrema in the sand class.

The correspondence between organism and sediment characteristics is best seen in the coarser materials: in sediments finer than Halimeda sand whole organisms become relatively scarcer and detrital fragments more important. However, organisms directly influence the characteristics not only of "primary" sediments (those formed by simple skeletal accumulation), but also of "secondary" sediments formed by the breakdown of whole skeletons and the accumulation of detrital fragments.

Many reef organisms do not break down gradually, giving a continuous sequence of sizes, but sharply and suddenly, in a manner determined less by the mechanisms of erosion than by the inherent structure and weaknesses of the skeleton (Wentworth and Ladd 1931, pp. 9-12). Thus, large coral heads do not become smaller and smaller under the influence of mechanical or chemical weathering, but after subaerial exposure are observed to fall apart by radial fracture into a number of pyramidal blocks, which in turn disintegrate into cuboidal fragments one inch across. These then break down directly into grit.

The process has been seen in Montastrea annularis, M. cavernosa, Diploria clivosa, and on one occasion in Colpophyllia natans. In the case of Acropora cervicornis the individual branches first lose their calices by mechanical weathering, then break down directly into grit. Halimeda segments apparently break into two or three fragments, and then directly into fine-sand or silt-size aragonite particles (though at Ifaluk in lagoon sediments Tracey and others found evidence of gradual breakdown: Tracey, Abbott and Arnow 1961, p. 65). Each of these breakdown stages is controlled by factors inherent in each particular organism, and this controls the resulting sediment characteristics to a degree second only to that of the original whole skeletons. The process of breakdown is also important, and is largely influenced by the point of lodgment of the particles in question: large particles lodged near the top of the beach will only be affected by chemical breakdown, whereas those of the foreshore will be affected by wave abrasion also. Discontinuous breakdown in cay sediments is explored in greater detail for A. cervicornis and Halimeda by Folk and Robles, but there is much scope for detailed investigation in the precise mode of breakdown in other reef organisms on islands.

Major Sediment Types

This section deals with the size, sorting and composition characteristics of six main types of sediments found on the British Honduras cays, particularly on Half Moon and Rendezvous Cays.

Beach sands

Beach sands are of two main types: coral grit sand, and Halimeda sand. These are composed of different organisms, have different size characteristics, and are found in different environments. Coral grit sand consists of equant, rounded, sometimes polished particles of coral, no longer specifically identifiable, and mollusc material, and subordinate amounts of red Homotrema which give a pinkish cast to the sand. Hoskin has stressed the usefulness of Homotrema as an environmental indicator, since it occurs in living-reef areas (Hoskin 1963). Echinoid spines and other materials are present in small quantity, with very small amounts of foraminifera. This sand concentrates in the No. [illegible] sieve (0.5Ø); at Half Moon Cay (Figure 3) 16 coral grit beach sands had a mean size of 0.09Ø, and mean sorting of 0.77Ø. Coral grit sands are found on more exposed cays, particularly on the atolls and southern barrier reef. The grit seems to represent a stable stage in the breakdown of larger coral colonies. Halimeda sands are of small importance in these more exposed cays.

Halimeda sands, which may consist of up to 100% Halimeda segments, are chiefly found on more protected cays, particularly on the north-central barrier reef between English and South Water Cays, where sand consists of both coral grit and Halimeda, and pure Halimeda beaches also occur. Patches of pure Halimeda, often in unsegmented clumps, are usually found high on the foreshore, where they are lodged by a selective sorting

process. Figure 4 shows cumulative frequency curves for eight Halimeda sands at Cay Glory, and Figure 5a curves for 11 Halimeda sands for Rendezvous Cay. In Figure 6, size is plotted against sorting for both groups. The sands tend to cluster round a mean size of 0Ø, with a sorting value of 0.6Ø (moderately good to good). Mean values (unweighted arithmetic means) for each group of sediments are:

	No. of samples	Mean size	Mean sorting
Cay Glory	6	-0.12Ø	0.64Ø
Rendezvous Cay 1961	11	+0.04	0.74
Rendezvous Cay 1962	7	-0.25	0.60

Halimeda segments appear more abundant in nearshore sands than in interior sands, possibly as the result of the greater mobility of flat, platey segments under wave action, and their selective concentration in the nearshore zone. The importance of Halimeda has been noted elsewhere on Caribbean beaches (Puerto Rico: Van Overbeek and Crist 1947; Jamaica: Steers and others 1940), and Folk and Robles (1964) estimate that this alga forms 50-70% of the sands of Isla Perez, Alacran. In the Pacific, however, Halimeda is most important as a sediment contributor on lagoon floors and is not important on beaches (Funafuti: David and Sweet 1904; Marshall Islands: Emery, Tracey and Ladd 1954; Kapingamarangi: McKee, Chronic and Leopold 1959).

Many sand-size constituents of cay sands are ill-adapted to sieve analysis because of their departure from spherical or equant form. Well-rounded coral grit appears to approach closest to "normal" quartz sands in shape, but other constituents, such as Halimeda plates, echinoid spines, spindle-shaped spicules, mollusc fragments and foraminiferal tests depart considerably from equant form. Plate-like algal segments, for example, bear no relation in weight or settling velocity to quartz spheres of comparable "diameter", and are lighter than many "finer" coral grits. This is explored in some detail by Folk and Robles: the limitations of the use of simple cumulative frequency curves derived from sieve analysis are thus apparent.

Beach shingle

All the data on beach shingle come from Half Moon Cay, where sediments up to -10Ø diameter are found, the coarsest formed by broken conglomerate-pavement blocks. The term "shingle", not used in the Wentworth scale, is commonly used by English writers for cobbles and gravel and is imprecisely defined; it here refers to coarse, highly permeable, interlocking coral fragments, derived with a minimum of breakage from colonies of living coral and other organisms, which are still specifically recognizable.

Of 53 samples for which cumulative frequency curves are given in Figure 2, the mean size is -7.46Ø and mean sorting 0.59Ø. Such figures cover much variation, and in particular the differentiation at Half Moon Cay of beach shingle into zones distinguished by size and color variation. The foot of a shingle beach is often formed by a discontinuous zone of coarse, rotted, yellow coral blocks; the foreshore

itself by a low but continuous ridge of fresh, white, small calibre shingle; and the beach crest by a zone of large, blackened coral blocks. The following table gives mean size of sediments in each zone at four transects across the beach on the south shore of Half Moon Cay; cumulative frequency curves for the same stations are given in Figure 7. For location of sampling stations, see Figure 14.

Black zone	(91)	7.42Ø	(85)	7.81Ø	(80)	8.10Ø	(75)	7.96Ø
White zone	(90)	6.37	(84)	6.46	(79)	6.75	(74)	6.93
Yellow zone	(89)	8.01	(83)	8.34	(78)	8.05	(73)	8.40

Figures in brackets are sample numbers

The fresh corals of the white zone are clearly being continually deposited by day-to-day wave action: wave competence is small, and therefore only small material is transported beachward. Mechanical abrasion is important in this zone. The larger blocks of the ridge crest must date from major storms: mostly they consist of little-damaged whole corals picked from the bottom and deposited on the beach crest: here they are exposed only to chemical and biological breakdown, and not to mechanical action. The ridge-foot blocks probably accumulate by transport across the reef flat during bad weather periods. Between the easternmost most exposed stations (73, 74, 75) and the more protected western stations (89, 90, 91), there is little lateral variation in calibre in either black or yellow zones, indicating approximately equal wave competence along the whole shore during storms; but calibre in the white zone decreases continuously from east to west, away from the seaward reefs, in response to decreasing wave energy as waves are refracted round the eastern point and travel westwards.

In addition to corals, large gastropods such as _Strombus gigas_ are locally important. At two stations, HMC 21 and HMC 54, _Strombus_ shells were separately measured.

Station	Number	Length	Breadth	
HMC 21	40	6.25	3.9	inches
HMC 54	25	7.2	4.7	inches

At HMC 54, of 100 measured pebbles and cobbles, [illegible] were whole _Strombus_ shells. Pumice occurs in smaller quantities in Half Moon Cay shingle ridges, and is of finer calibre: at HMC 91a, the mean diameter of 100 pumice pebbles was 0.9[illegible] inches, and the largest cobble seen had maximum dimensions of 4 inches. No data are available on the breakdown of pumice pebbles, which probably proceeds by attrition of the pebbles and production of grit; but collection of _Strombus_ fragments in an area of strong wave activity suggests that breakdown is gradual, producing a wide range of particle sizes and shapes.

Interior sands

Away from the beaches the character of cay sediments changes, color changing with humus formation, and calibre with the breakdown of particles and accumulation of fines during the soil-forming process. At Half Moon Cay soil-formation has proceeded furthest where the vegetation cover is densest. Almost all the beach sediments contain a negligible silt fraction (i.e., finer than +3.75Ø). Under the eastern coconut plantation at Half Moon, silt content varies from 0.1 to 0.6%; while under the Cordia-Bursera woodland this rises to 1.0-3%. The maximum silt fraction of 4.95% is found at HMC 113 (Figure 14). The silt fraction consists of brown material which does not dissolve in dilute HCl; it generally appears in sieve No. 22 and increases in relative quantity through No. 200; at all stages it is quite distinct from the white carbonate grains. The larger coral grit grains can be seen to be pitted and infilled with this material.

Figure 3 compares cumulative frequency curves for 16 beach and 26 interior sands at Half Moon Cay, and Figure 8 plots size against sorting for both these sets of data. Size and sorting means for the two groups are as follows:

	Number	Mean size	Mean sorting
Beach sands	16	+0.09Ø	0.77Ø
Interior sands	26	+0.44	0.78

There is no difference in sorting between the two groups, but the interior sands are considerably finer than the beach sands. This is probably the result of breakdown of sand particles by soil forming processes under a vegetation cover. On small cays without a vegetation cover, such as Cay Glory, these differences between beach and interior sands are not found.

Dune sands

Dune sands are a special type of interior sands, characterised by fineness, but consisting, like beach and interior sands, of coral grit, Homotrema and mollusc fragments. Figure 9 gives cumulative frequency curves for dune sands from Half Moon Cay (HMC 55), Ambergris Cay (three samples), and Northern Cay (Lighthouse Reef). These sands are all finer than normal interior or beach sands (compare Figure 3), but the samples at Northern Cay, where the dunes are most extensive, is also exceptionally well sorted (mean size +1.59Ø; mean sorting 0.35Ø). The position of the cumulative frequency curves compared with normal beach and interior sand curves suggest that there is a real difference between the two groups, which may be diagnostic of origin in cases where this is uncertain, as at Ambergris Cay. However, the number of samples collected is too small to reach any conclusion: dune areas are uncommon on the British Honduras reef islands.

Hurricane deposits

Qualitative data on hurricane deposits have already been presented for a large number of islands (Stoddart 1963). In 1962, following Hurricane Hattie, sand samples were taken on Rendezvous and Half Moon Cays at locations sampled in 1961 before the hurricane. It was not possible in 1962 to carry out any measurements of shingle deposits, and where, as a result of the storm, sand was overlaid with shingle, and vice versa, no comparison is possible. Sand-size hurricane deposits were less well sorted than normal beach deposits, and microscopic examination showed the presence of many organisms, mainly gastropods, pelecypods and foraminifera, not normally seen in beach sands. These fairly uniform sands were spread over large areas of cay surfaces, and were not confined to foreshore areas. They probably originated in reef-flat sand deposits, which were transported landward and roughly sorted by the storm waves. The following table summarizes changes at Rendezvous and Half Moon Cays 1961-2, and the Rendezvous Cay frequency curves for 1961 and 1962 are given in Figure 4. Figure 10 plots mean size and sorting of pre- and post-hurricane sands at Half Moon Cay.

	Year	Number	Mean size	Mean sorting
Rendezvous Cay	1961	11	+0.04Ø	0.74Ø
	1962	7	-0.25	0.60
Half Moon Cay	1961	16	+0.09	0.77
	1962	28	+0.69	0.92

The apparent anomaly, that Rendezvous sands in a protected situation are coarser than the Half Moon sands on an exposed cay, is explained by the fact that the former are *Halimeda* sands and the latter coral grits.

Underwater sands

By contrast to beach sands, underwater sands consist of a large range of grain sizes corresponding to local organic production, and in the absence of wave action are poorly sorted. In general, sorting will be poorer in more protected locations. Figure 11 gives cumulative frequency curves for sediments from the leeward reef flat, Glover's Reef, from southern lagoon, Turneffe Islands, and from the anchorage at Rendezvous Cay, for which size and sorting are summarized in the following table:

	Mean size	Sorting
Glover's Reef (Bushy Spot)	+0.00Ø	0.92Ø
Turneffe (southern lagoon)	+0.65	2.18
Rendezvous Cay A1	-0.80	0.70
Rendezvous Cay A2	+0.29	1.03

Samples are quite insufficient in number to make any detailed comparison of above and underwater sedimentation on the reefs; for a very detailed study of mainly underwater sedimentation at Alacran, see Hoskin (1963).

Sediments of Half Moon Cay

Data for 155 samples at Half Moon Cay are sufficient to map the distribution of sediment characteristics (Figure 12); the samples are well distributed except in the Cordia- Bursera woodland (Figure 13). At the east end of the cay, close to the seaward reefs, and again along the south shore, the beach is built of shingle coarser than -6Ø but generally less coarse than -8Ø. These are both areas of high wave energy, and high coral productivity close inshore. In both areas there is a well-marked zonation into yellow, white and black zones, with distinctive calibre. In the yellow and black zones calibre tends to be uniform irrespective of location along the beach, but gradation is found in the white zone in response to changes in wave energy. Two patches of -9 to -10Ø sediment on the southeast beach are formed by accumulations of broken beach conglomerate slabs.

Beach sands are generally fairly coarse (1Ø or 0.5 mm), though finer than the Halimeda sands of Rendezvous Cay. Over most of the cay surface, sands under coconuts are coarser (0.5 to 1Ø) than those under dense woodland (0 to 0.5Ø). This probably results from wind-winnowing of fines in the former area, leaving a fairly coarse surface lag, and from increased breakdown by chemical and biomechanical means in the woodland. Within the woodland the surface is littered with old, blackened and rotted coral blocks in the size range -5 to -8Ø.

Sorting varies less regularly. The coarser material on the beaches is in general best sorted, with values along the south shore and at the east point of less than 0.5Ø. Excellent sorting is found in some shingle along the south shore (0.29 to 0.3Ø), in dune sands at the south point (0.26Ø), and in conglomerate block accumulations (0.21Ø). Bare sand under coconuts is moderately sorted, with values ranging from 0.7 to 0.85Ø, in contrast to beach sands, which have a fairly uniform sorting value of 0.5 to 0.6Ø. Under the dense woodland, where the sand is often mixed with coral blocks and the sediments are bimodal, sorting is poor, with values in excess of 1.0Ø. The sand alone in these areas is as well sorted as under the coconuts.

The variation in silt content has already been noted. Silt (finer than +3.75Ø) is only appreciable (more than 1%) under the Cordia-Bursera woodland, reaching a maximum of nearly 5%: elsewhere it is negligible.

For notes on such erratic sediments as brown limestone and pumice, see Stoddart (1962, pp. 105-106); the same paper also describes consolidated sediments on Half Moon Cay.

Size and Sorting

When all values of size and sorting at Half Moon Cay are plotted against each other in Figure 15, certain broad relationships are seen. The best sorted sediments are the coarsest and the finest. This is very well seen in the shingle sector, where sorting gets progressively better

as size increases from -5 to -10Ø. The best sorted sediments (sorting less than 0.5Ø) are those grouped near a mean size of -3Ø. This trend is probably partly due to the narrowing range of organisms as size increases: the -3Ø sediments consist largely of small brain corals and Acropora palmata slabs. In the sand-size sector the scatter of size and sorting is greater, but there is a tendency for sorting to improve with decreasing calibre from -1Ø to +2Ø. It has already been seen that Halimeda sands at Rendezvous Cay, with a mean size of 0Ø, have a sorting value of 0.6Ø (Figure 5).

At Isla Perez, Alacran, Folk (1962) has demonstrated a sinusoidal relationship between size and sorting in the size range -3Ø to +2.5Ø, with best-sorting peaks at mean sizes of -3Ø, 0Ø and +2Ø. Each peak corresponds with the modal size of a particular organic constituent: the -3 to -4Ø peak with Acropora cervicornis branches, the 0Ø peak with Halimeda sand, and the 2Ø peak with coral grit. At Isla Perez, sediments with mean sizes between those which correspond to peaks for each particular organic group have been shown to contain more than one type of sediment, with correspondingly poorer sorting. In general, Folk's hypothesis is fully confirmed by the British Honduras data, though details vary. The absence in Honduras of sediments in the -1 to -5Ø range rules out direct comparison with Folk's curves, and in the Honduras data sorting values are less good for both Halimeda sand and coral grit than at Alacran. The Half Moon coral grit (mean size +1Ø) is considerably coarser than the dominantly +2Ø grit at Isla Perez.

Sorting values for both sand and shingle at Half Moon Cay have been plotted as cumulative frequency curves in Figure 16, which may be compared with Folk's similar figure for Gulf of Mexico carbonate sands (Folk, 1962, p. 241). Shingle is consistently better sorted than sand (0.53Ø against 0.74Ø) and the mean sorting of all sediments is 0.61Ø. This compares with 0.47Ø for Folk's carbonate beach sands. It is interesting that sorting is so closely comparable on adjacent beaches where calibre may vary over the range from +2Ø to -10Ø (¼ to 1024 mm). Submarine deposits appear to be very much more poorly sorted.

Conclusion

The data reported here are sufficient to add some definition to the concept of ecological field units suggested by Cloud, insofar as these have been used as a field survey technique in British Honduras. Sediments of diffent calibres are shown to have sharply defined size and sorting characteristics, and also to be characterized by regular organic derivation. Hence, the field units can be readily defined in terms both of size and composition, the two attributes together being directly related. Future field mapping can thus use terms such as cervicornis shingle, Halimeda sand, and coral grit sand, with the knowledge that the attributes of each group are fairly stable in terms of size, sorting and composition, and are mutually distinct. Because this survey was not designed specifically to study the sediments, this analysis is carried no further: a sampling plan could readily be devised to test these points and establish their significance.

The results also in large measure confirm the original work by Folk at Alacran and Isla Mujeres, where he showed that size and sorting depend less on wave energy than on organic composition. Wave energy controls mean size (i.e. the type of organism present), and the type of organism then controls sorting.

There is clearly further scope for (a) specific design for further sediment study both above and below water on the British Honduras cays, to test the relationships of size, sorting and other sediment characteristics to organic composition and wave energy, and the nature of the interlocks between them; (b) for experimental studies on breakdown under wave action of different types of organic carbonate skeletons; and (c) for studies of the effect of diverse size and shape characteristics on mobility under water and on the foreshore. To a large extent, the solution of these problems involves a fourth, (d) the derivation of meaningful measures of size and shape for reef-derived carbonate particles.

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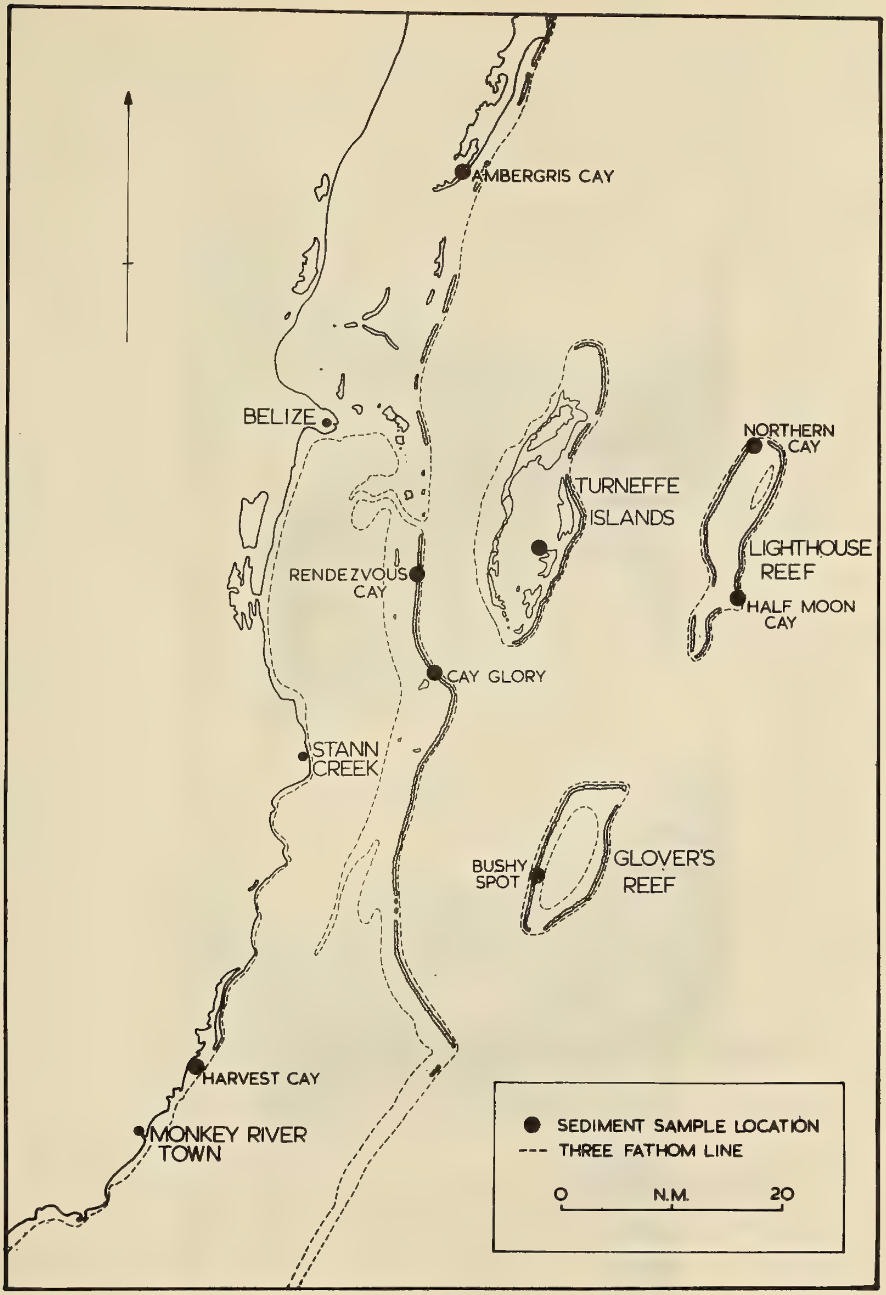

Figure 1. British Honduras: location of areas sampled

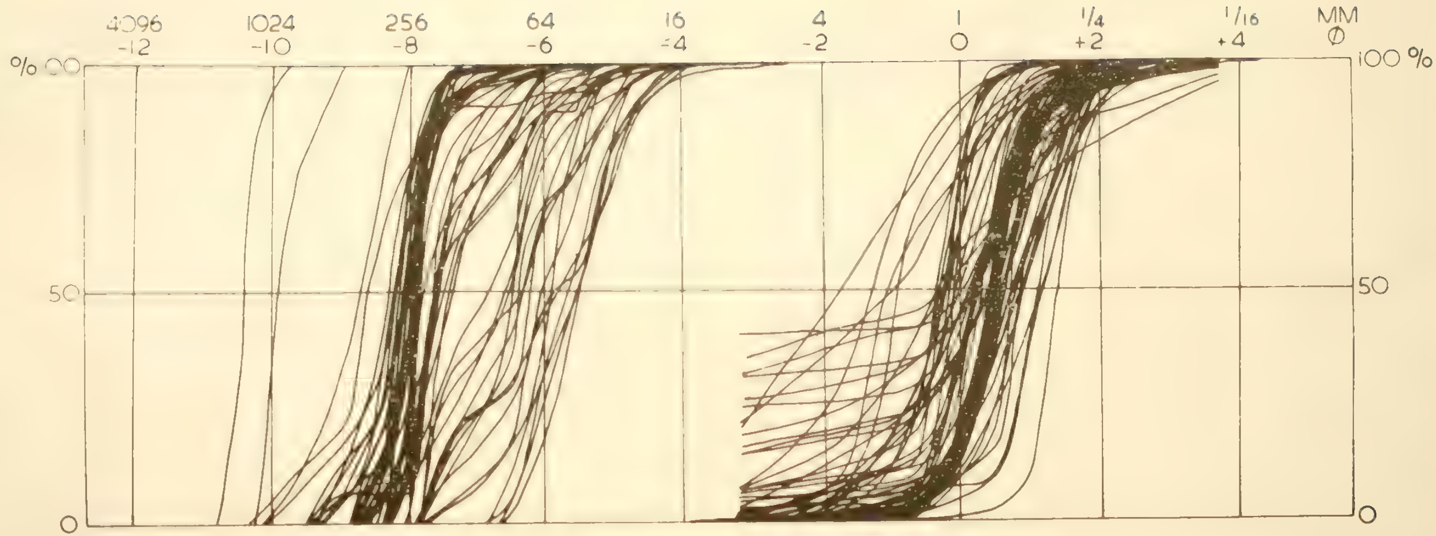

Figure 2. Cumulative frequency curves for 115 Half Moon Cay sediment samples

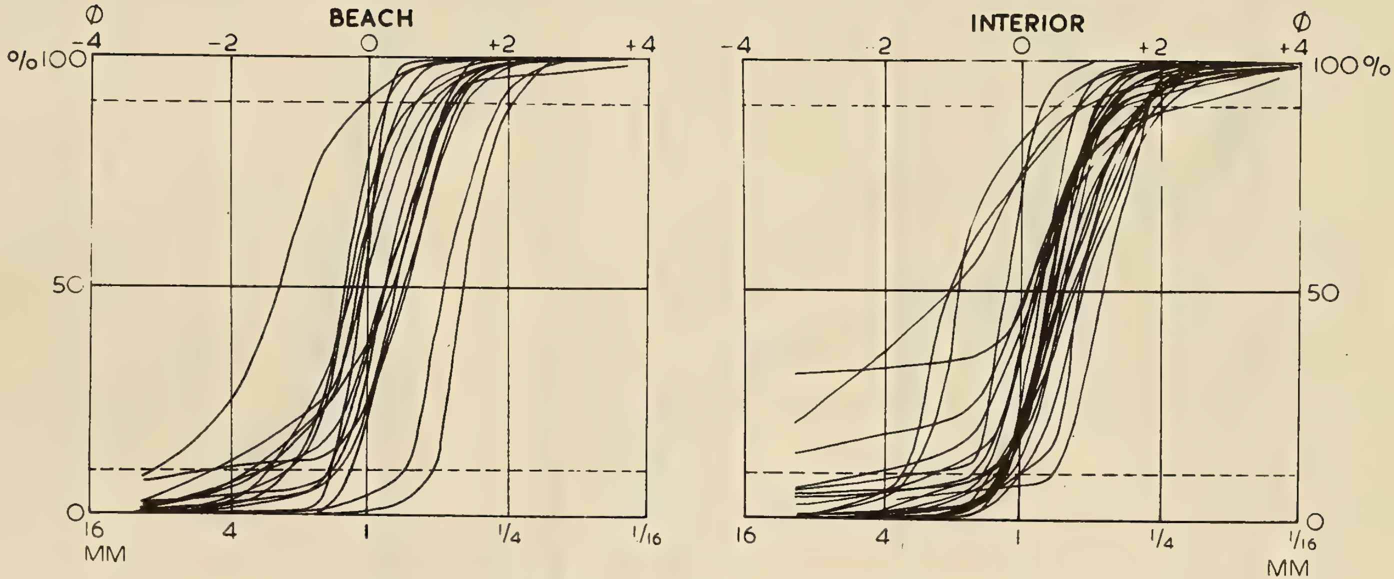

Figure 3. Cumulative frequency curves for 16 beach and 26 interior sands at Half Moon Cay

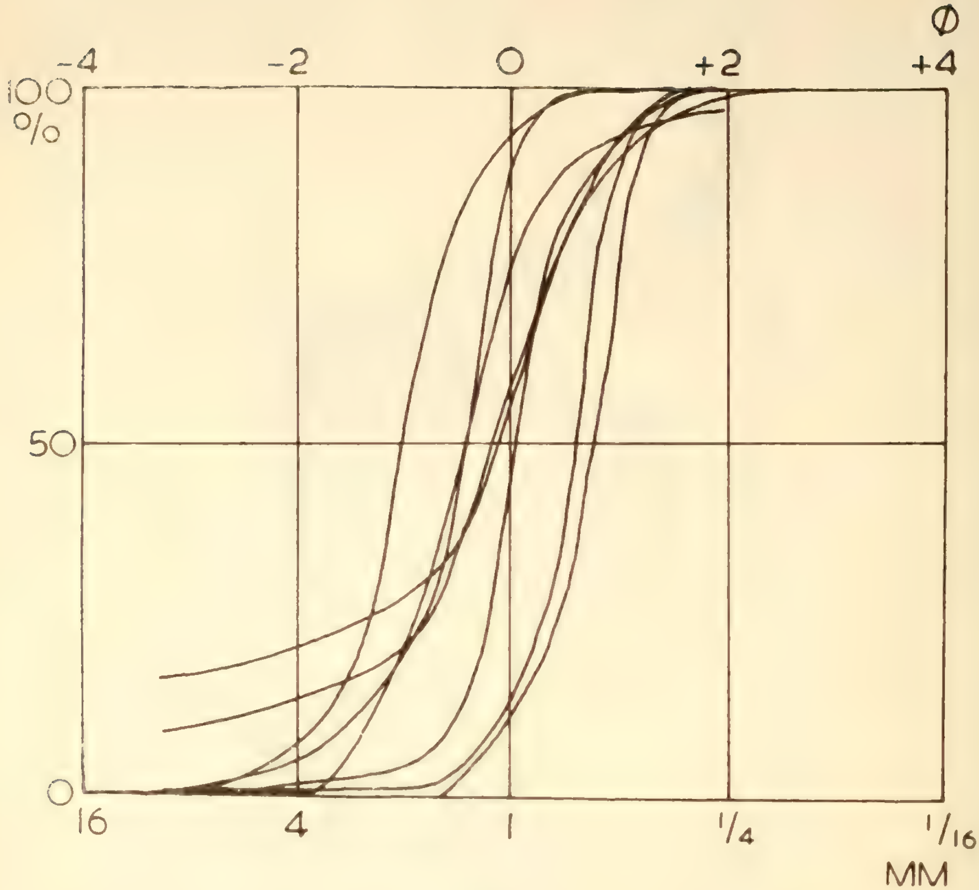

Figure 4. Cumulative frequency curves for 8 Cay Glory *Halimeda* sands

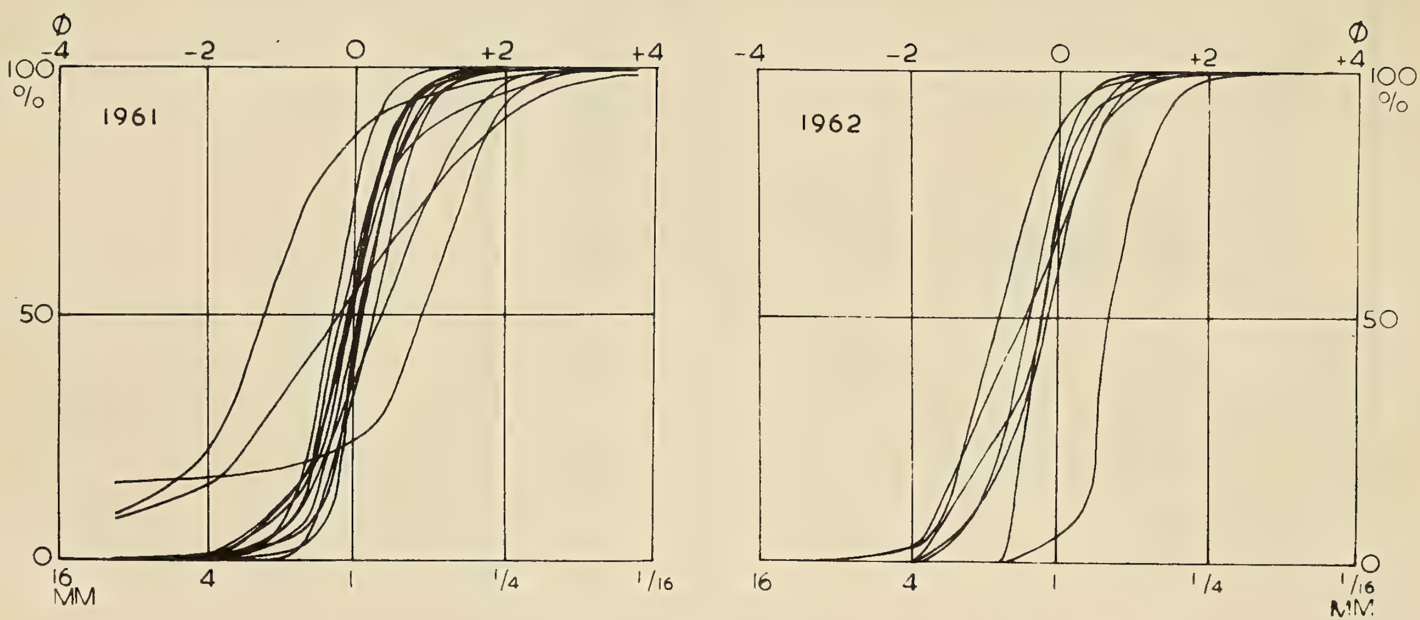

Figure 5. Cumulative frequency curves for 13 *Halimeda* sands in 1961 and 7 in 1962 from Rendezvous Cay

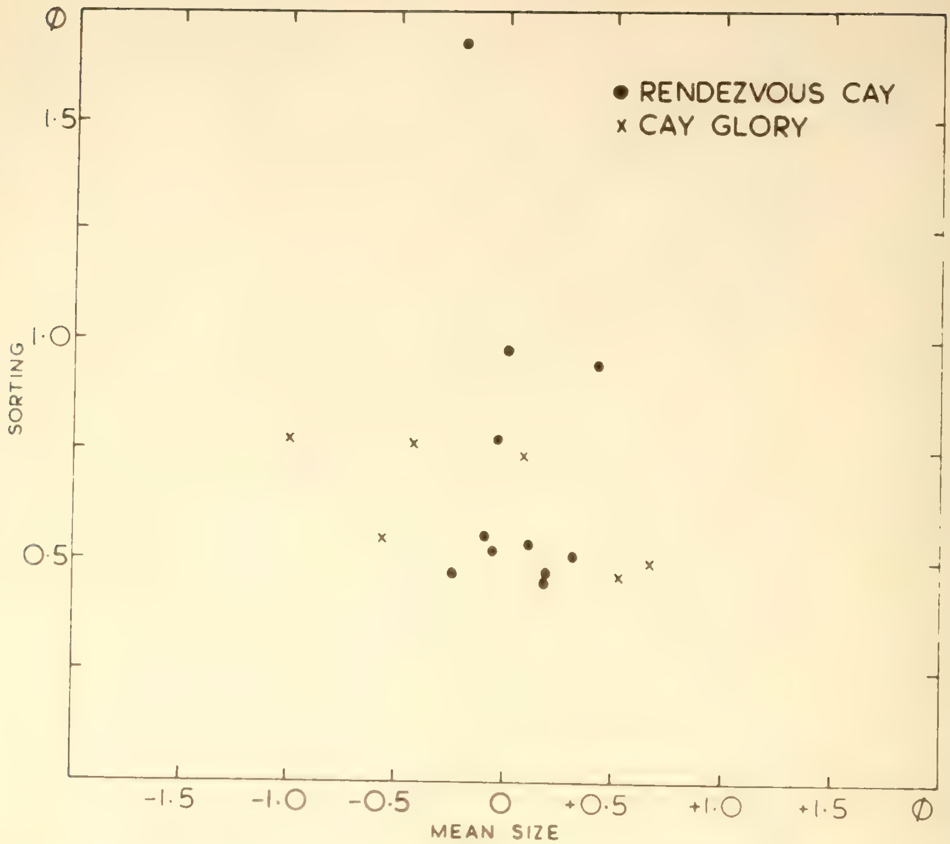

Figure 6. Mean size and sorting of Rendezvous Cay and Cay Glory beach sands

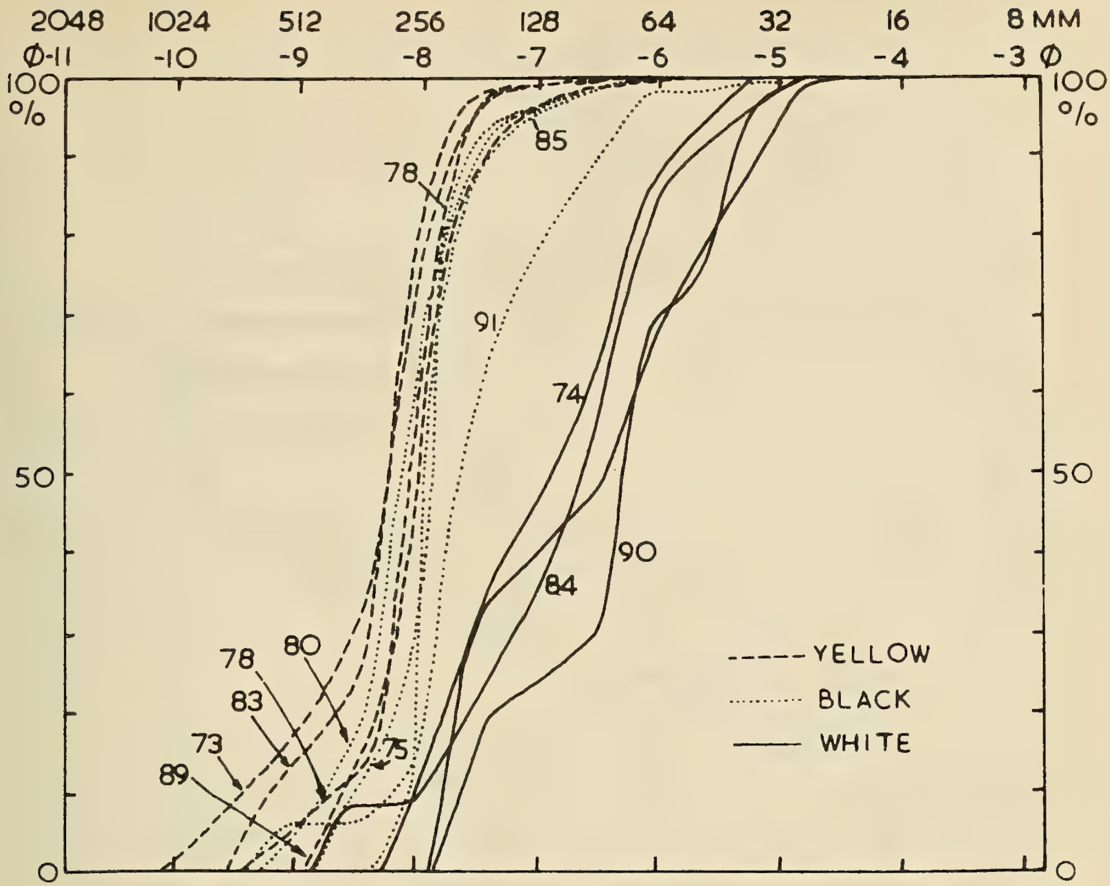

Figure 7. Cumulative frequency curves for yellow, white and black shingle zones, south shore of Half Moon Cay

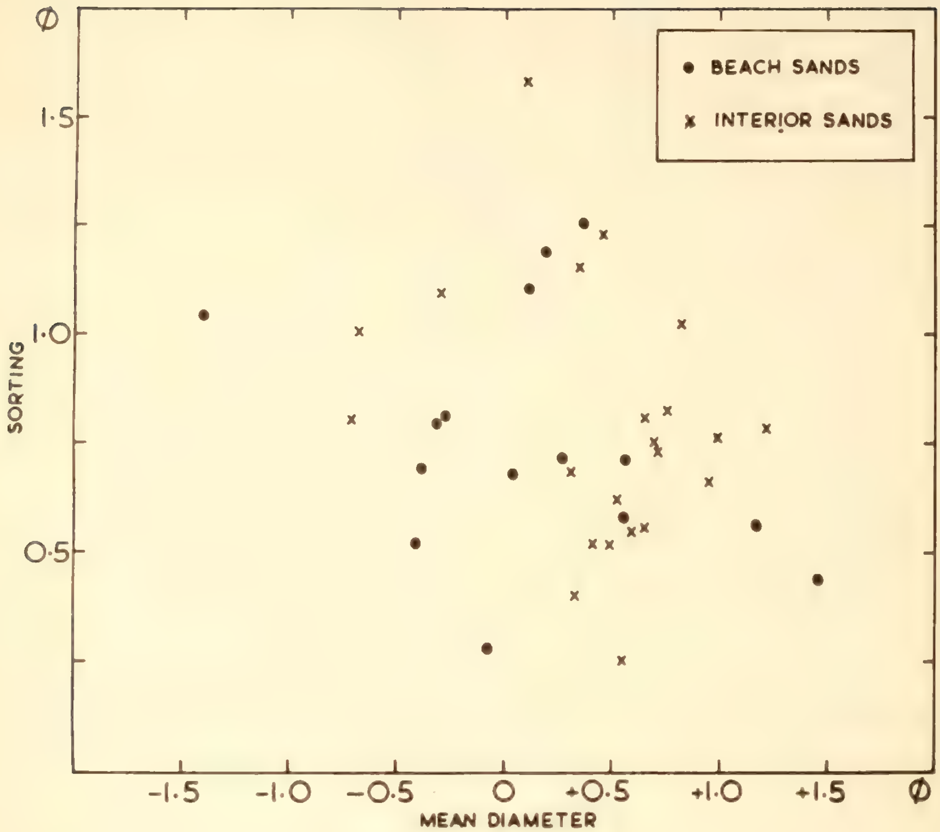

Figure 8. Mean size and sorting of Half Moon Bay beach and interior sands

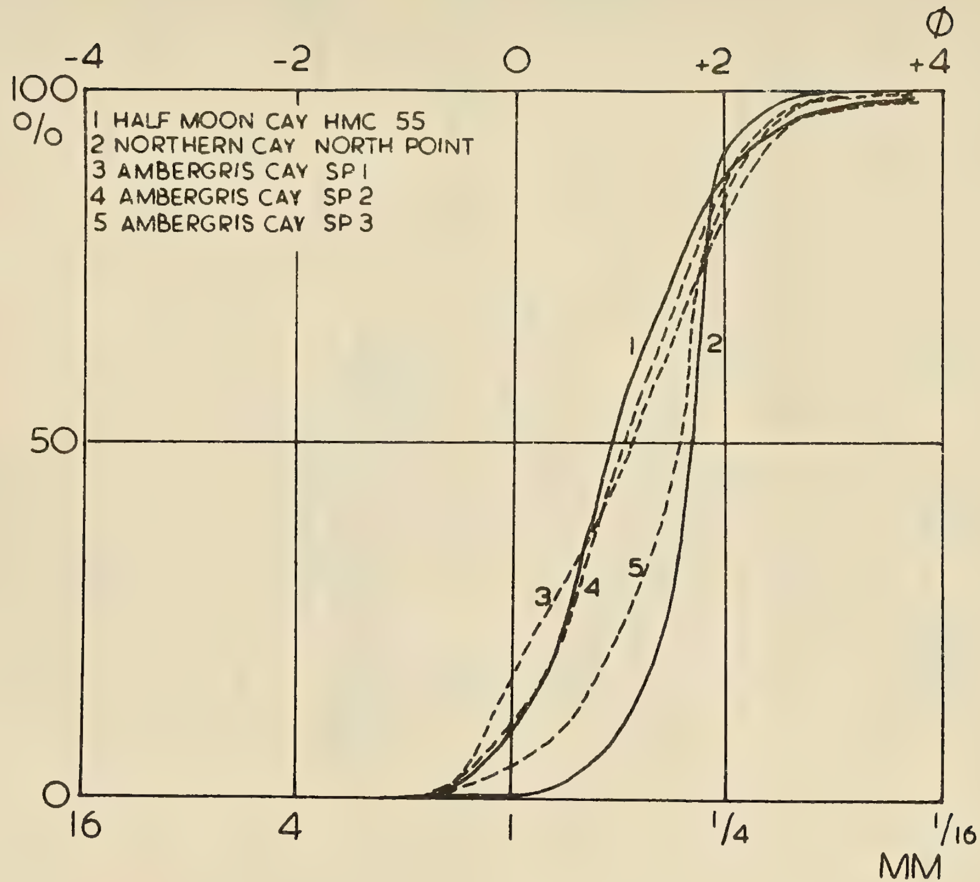

Figure 9. Cumulative frequency curves for dune sands

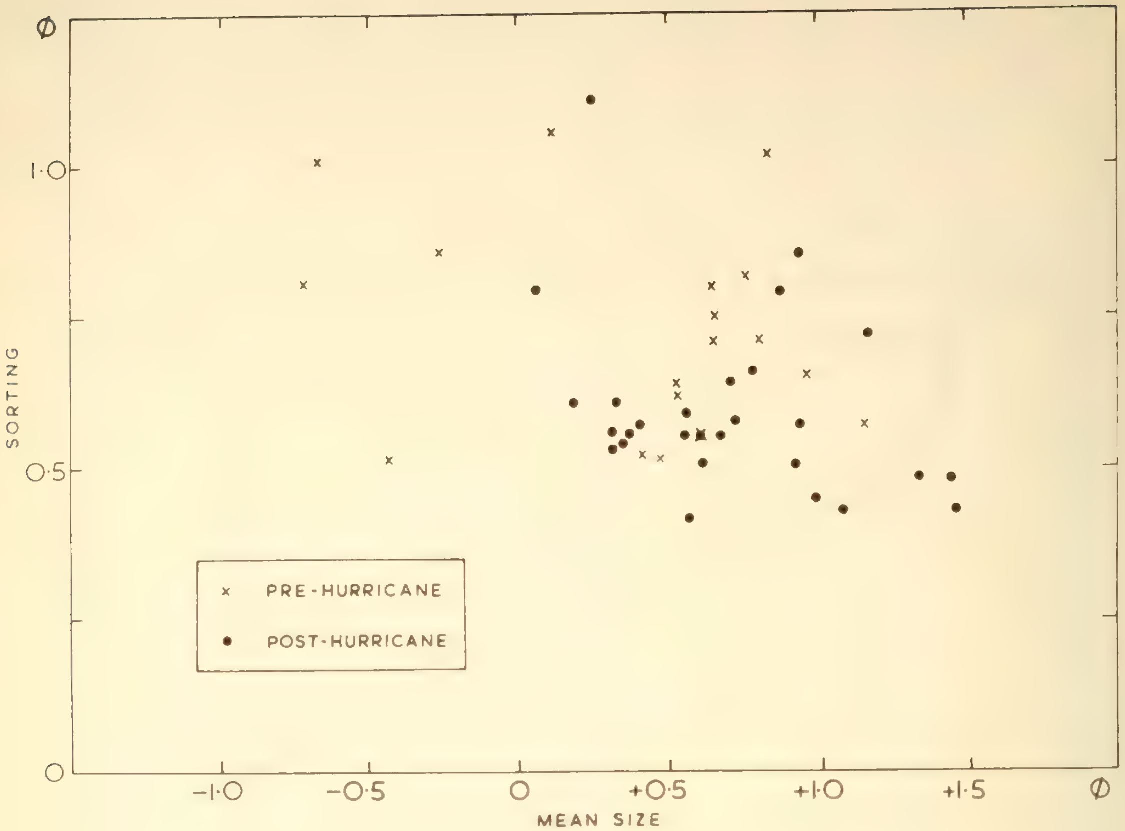

Figure 10. Mean size and sorting of pre- and post-hurricane sands at Half Moon Cay

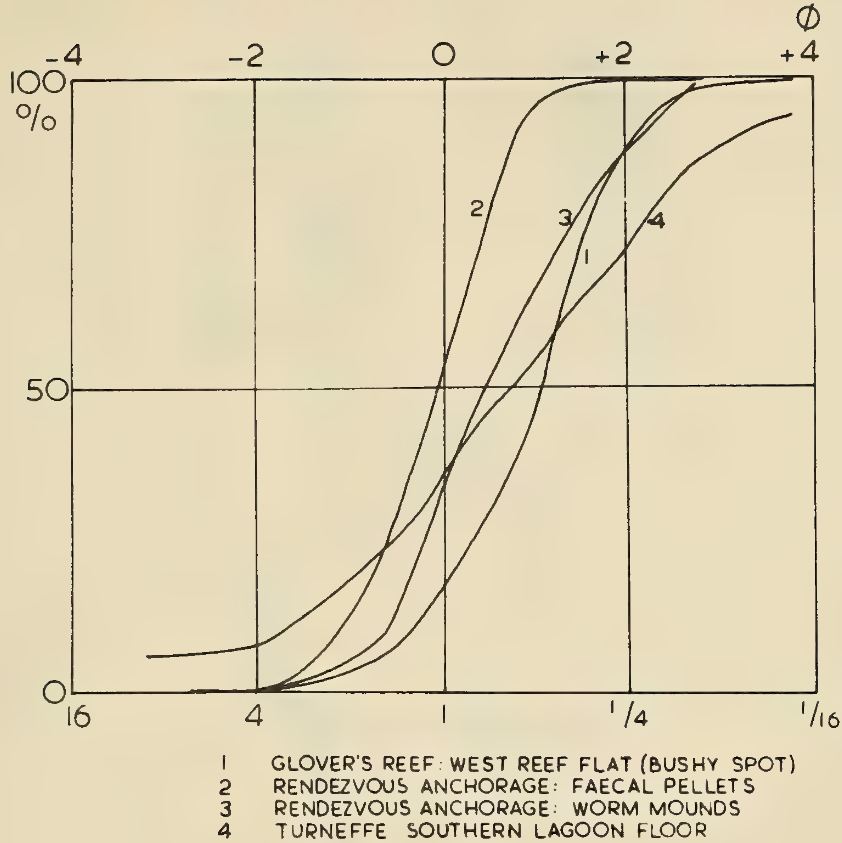

Figure 11. Cumulative frequency curves for underwater sediments

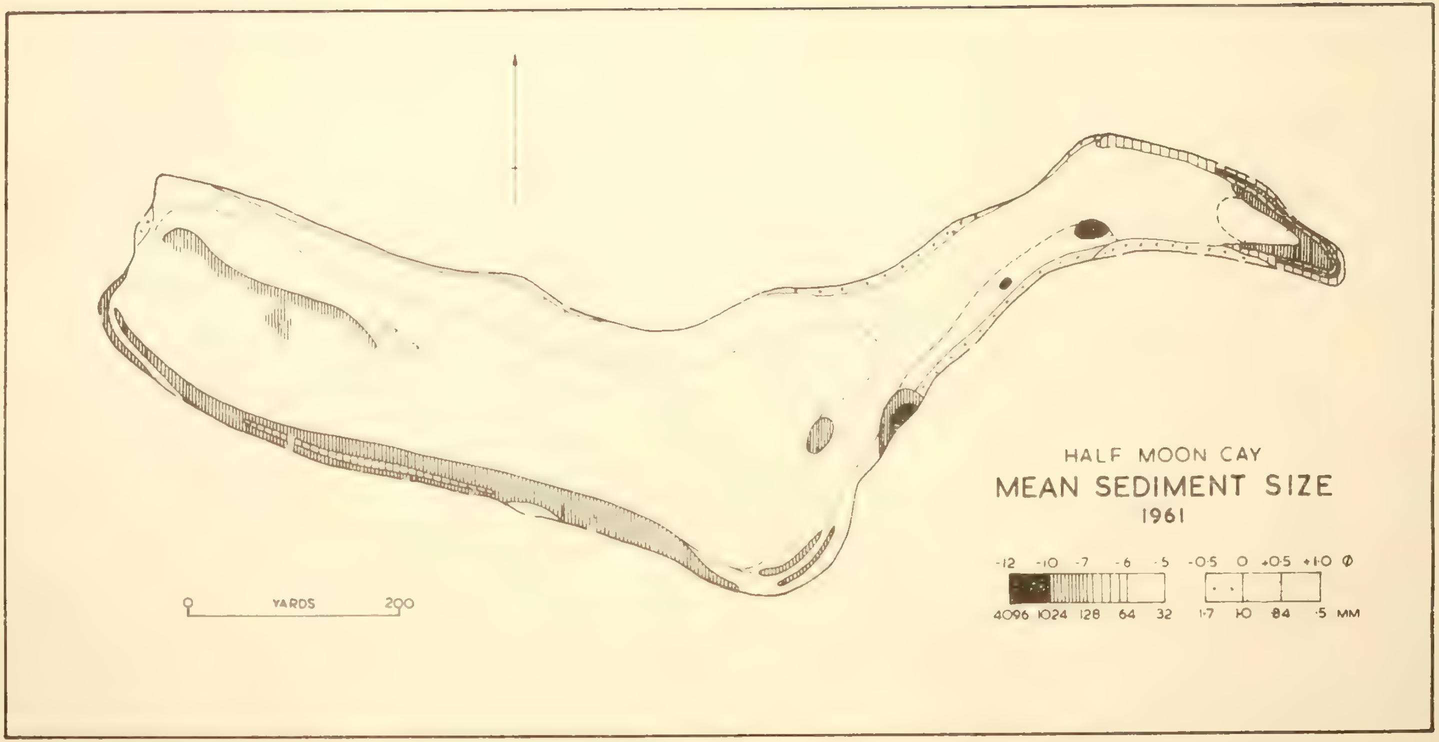
HALF MOON CAY
MEAN SEDIMENT SIZE
1961
-12 -10 -7 -6 -5 -0·5 0 +0·5 +1·0 Ø
4096 1024 128 64 32 1·7 1·0 ·84 ·5 MM
0 YARDS 200

Figure 12

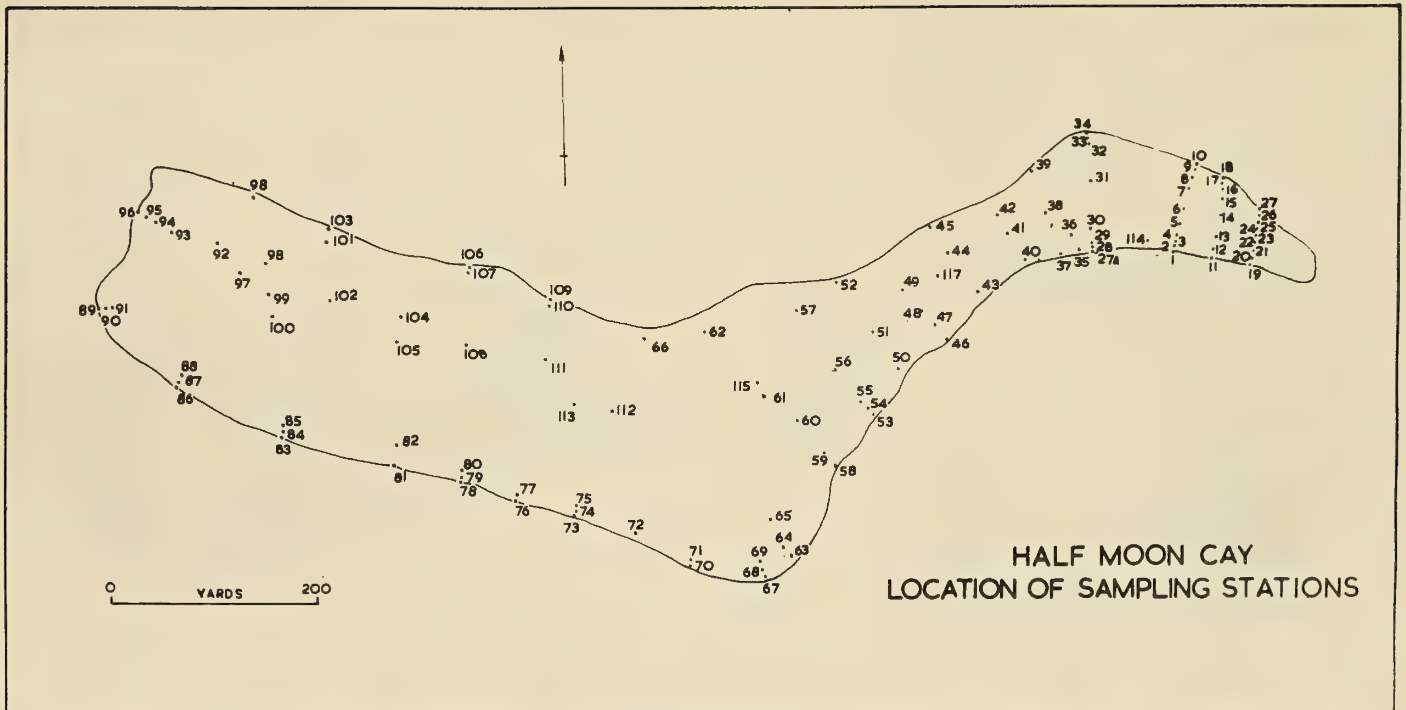

Figure 13

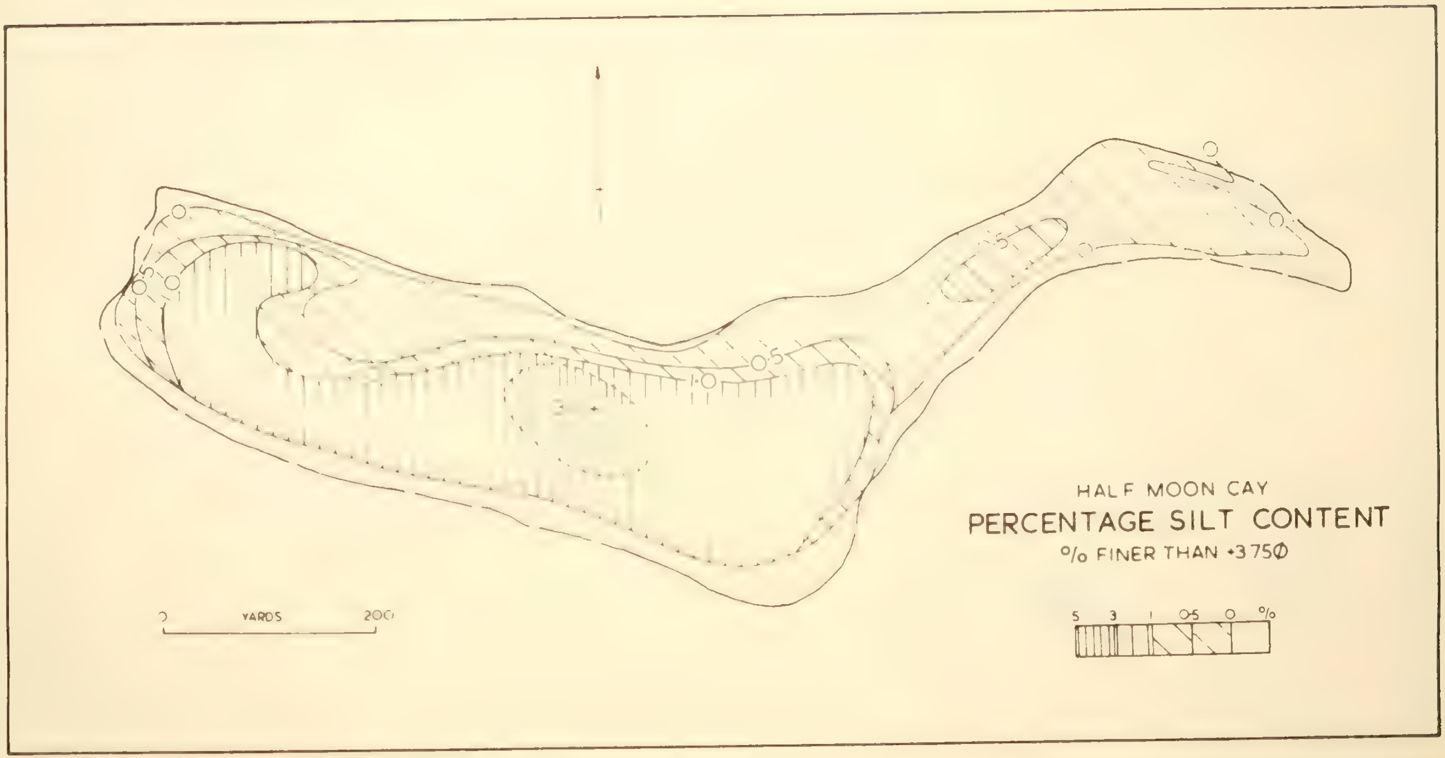
HALF MOON CAY
PERCENTAGE SILT CONTENT
% FINER THAN +3.75Ø
5 3 1 0.5 0 %
0 YARDS 200
0.5
1.0
3

Figure 14

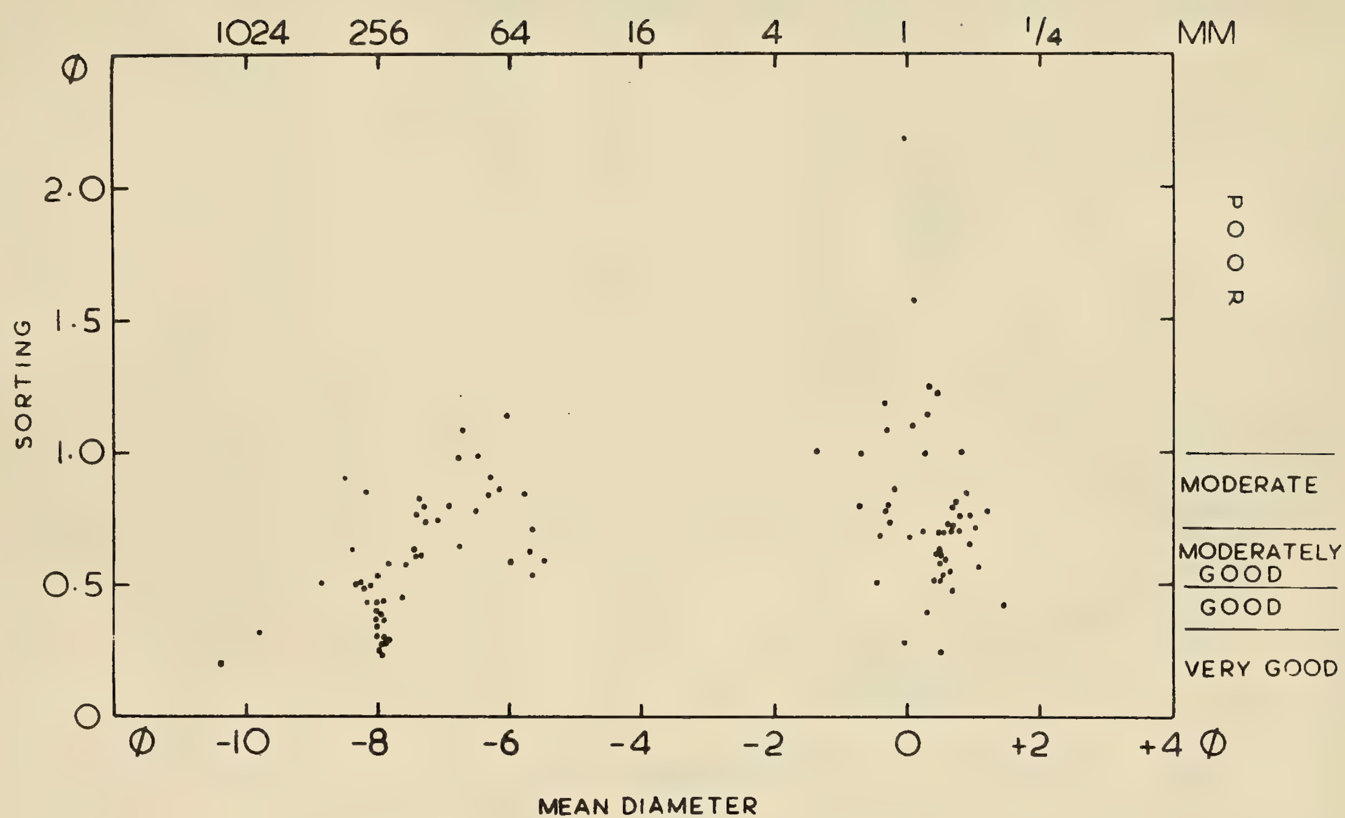

Figure 15. Mean size and sorting of Half Moon Cay sediments

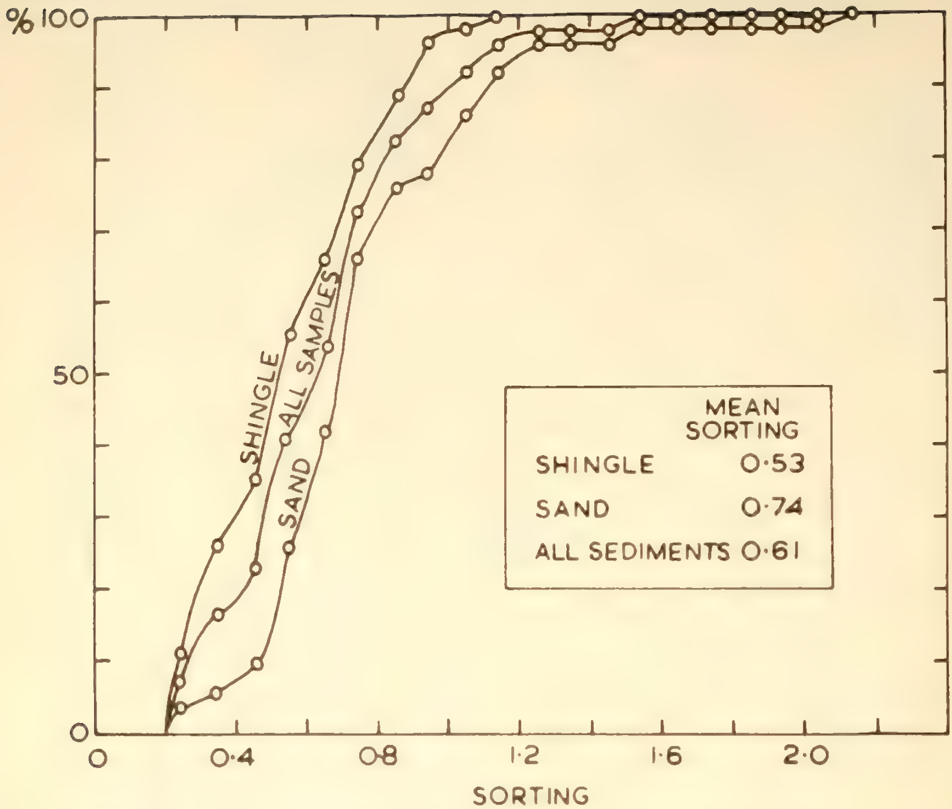

Figure 16. Frequency curves of sorting in sand and shingle sediments at Half Moon Cay

ATOLL RESEARCH BULLETIN

No. 105

Floristic report on the marine benthic algae of selected islands in the Gilbert Group

by

Roy T. Tsuda

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Floristic report on the marine benthic algae

of selected islands in the Gilbert Group[1/]

by

Roy T. Tsuda[2/]

The Gilbert Islands are a part of the Gilbert and Ellice Islands Crown Colony of Great Britain. They lie in the Pacific Ocean directly southeast of the Marshall Islands and are located between the parallels of 2°45' S. and 3°30' N. latitude, and the meridians of 172°30' E. and 177°15' E. longitude. All of the islands in this group are low islands related to atolls. They are inhabited by Micronesian and Melanesian people who are greatly dependent on materials from the sea for food.

Past experiences by the natives have been (Cooper, 1964) that certain species of reef fishes when eaten are extremely toxic in one area and nontoxic in another area. Because fish is one of the primary diet items of the natives, various investigations have been undertaken to find the causes of this toxicity which applies specifically to fishes inhabiting reefs. Only reef fishes from certain areas are affected, therefore it seems (Randall, 1958) that a likely cause of this toxin lies in their food or habits. Since Helfrich & Banner (1963) have shown that the toxin can be transmitted through the food chain, and is likely (Helfrich, et al., ms.) to be transmitted to the large carnivores by bottom feeding herbivores, the marine algae, especially the small filamentous species, head the list as the most likely sources of the toxin.

At present, a study is underway at the Hawaii Marine Laboratory, under the direction of Drs. Albert H. Banner and Philip Helfrich[3/], to further investigate the "toxic reef fishes" in the Pacific area. One of the principal steps associated with this project is to identify the marine algae associated with various "toxic" situations.

Of the sixteen islands in the Gilbert Group, only for Onotoa Atoll has anything extensive been published on the algae. This is the 1957 "Preliminary Report on the Flora of Onotoa Atoll," wherein Moul gives a list of the algae he collected from this atoll, the identification to species having been done by Moul, except for the Myxophyta which were identified by Dr. Francis Drouet[4/]. In Appendix I of his

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[2/] Botany Department, University of Hawaii, Honolulu, Hawaii; work done and supported in part by funds provided by contract (GB404), between the University of Hawaii and the National Science Foundation.

[3/] University of Hawaii, Honolulu, Hawaii.

[4/] Academy of Natural Sciences, Philadelphia, Pennsylvania.

"Report on the Gilbert Islands: Some Aspects of Human Ecology," Catala gives (1957) a list of algae (all Myxophyta) collected by his wife in July 1951. These were also identified by Dr. Drouet. Catala's algae were collected in fish ponds from only two islands, from the northern and southern fish ponds on Nukunau and from a fish pond on Beru. There has been no extensive collection of algae from the other islands of the Gilbert Group. Dr. V. J. Chapman (1955) has published a list of the algae collected from Funafuti Atoll, in the Ellice Group which is south of the Gilbert Group.

Mrs. Jane Cooper[5] sent some bottles of preserved algae collected from six of the islands of the Gilbert Group in areas where the fish were toxic or nontoxic. These were sent to the University of Hawaii at the request of Drs. Banner and Helfrich and thus provided an opportunity for the author to extend our knowledge of algal floristics in the Central Pacific and at the same time contribute some phycological information specifically useful to the poison fish studies. The first step undertaken was to sort the algae in each collection into their respective genera and give each entity from each collection a number. The numbers run from 18771 to 18952 and are permanently recorded in Dr. Maxwell S. Doty's[6] notebook number [illegible]5. The specimens themselves are being deposited in Dr. Doty's herbarium.

In identifying the algae, particularly those species within the Rhodophyta, and in citing bibliographies of original publications, Dawson's (195[illegible], 1956) papers have been the most useful. Other references which proved of immense value while working with the present Chlorophyta are Egerod's (1952) paper on the siphonaceous algae, Eubank's (1946) paper on _Caulerpa_, Dr. William J. Gilbert's[7] (unpub.) field manual of Hawaiian Chlorophyta, and Hillis' (1959) paper on _Halimeda_. The manuscript manual on Hawaiian Phaeophyta by Dr. Doty and Mr. W. Jan Newhouse[8] has been primarily used in identifying the species of Phaeophyta.

The following is a list of the atolls and the algal habitats of each of the Cooper collections from the Gilbert Group. Reefs inhabited by "toxic fishes" are designated for convenient reference here as "toxic reef flats," or "toxic areas." Cooper (1964) provides a more complete discussion of these areas.

ABEMAMA ATOLL, Abemama Island (0°21' N. lat., 173°51' E. long.): passage between ocean and lagoon at low tide in about three feet of water along the eastern side of the island at the Government Village, July 1962 (18895-18898, 18900, 18902, 18903).

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6/ University of Hawaii, Honolulu, Hawaii.

7/ Albion College, Albion, Michigan.

8/ Dole Corporation, Honolulu, Hawaii.

MARAKEI ATOLL, Marakei Island (2°03' N. lat., 173°25' E. long.): "toxic reef" south of Rawanawi Village, below low water mark, July 1962 (18771-18786); "toxic reef", taken from the top of rocks below low water mark which do not quite dry out but have a few inches of water on them at low tide, July 1962 (18787-18793); "toxic reef flat" south of Rawanawi Village, July 1962 (18794-18800, 18940-18943, 18946); "toxic area" south of Rawanawi Village, stones from bottom of surge channels which are twenty to thirty feet deep, July 1962 (18905-18909, 18911, 18912, 18919, 18921, 18922, 18926, 18927, 18930); "toxic reef" near the Village of Rawanawi, July 1962 (18936-18938).

NONOUTI ATOLL, Nonouti Island (0°49' S. lat., 174°29' E. long.): ocean reef flat subject to continual heavy surf, July 1962 (18888-18890).

NUKUNAU ATOLL, Nukunau Island (1°19' S. lat., 176°23' E. long.): "toxic reef" near the Village of Rungata, July 1962 (18892-18894).

TAMANA ATOLL, Tamana Island (2°39' S. lat., 175°58' E. long.): bottom and side of newly blasted channel in the reef, July 1962 (18948, 18952).

TARAWA ATOLL, Betio Island (1°30' N. lat., 173°00' E. long.): western reef with an area of mostly sand, July 1962 (18801-18804, 18817-18825); southern reef near shoreline with a large sandy pool with few algae present, July 1962 (18805-18810, 18826-18833, 18884-18886); southern reef at western end which borders the ocean and dries out at low tide, July 1962 (18835-18845); southern reef below low water mark exposed to heavy surf, July 1962 (18857-18859); southern reef in a small tide pool on the ocean edge which does not dry out, July 1962 (18850-18856); northwest reef which is a "toxic area" of coarse sand and stones with a strong current, July 1962 (18811-18816); western reef with dazzling white sand and a few large stones covered with algae, July 1962 (18860-18862, 18864-18866); lagoon beach which is sandy with small stones and large sting ray holes, June 1962 (18867-18874); beach reef in lagoon about three feet below low water mark, June 1962 (18875-18883).

The following is an annotated list of the blue-green, green, brown, and red algae found in the collections from the islands in the Gilbert group listed in the above paragraphs. The collection numbers for the specimens are listed with the species. Annotations have been restricted merely to pertinent taxonomic and ecological information which the author thought of particular value.

MYXOPHYTA

Calothrix crustacea Thur.

Tarawa: 18807A (epiphytic on *Padina*).

Entophysalis deusta (Menegh.) Drouet & Daily

Tarawa: 18816.

Hormothamnion enteromorphoides Grun.

Marakei: 18796, 18797.

Hydrocoleum cantharidosmum (Mont.) Gom.

Marakei: 18797; Tarawa: 18872.

Hydrocoleum lyngbyaceum Kütz.

Marakei: 18796.

Lyngbya aestuarii (Mert.) Lyngb.

Marakei: 18795, 18796, 18807A (epiphytic on Padina).

Lyngbya lutea (Ag.) Gom.

Marakei: 18781; Tarawa: 18883.

Lyngbya semiplena (Ag.) J. Ag.

Marakei: 18781.

Mastigocoleus testarum (Lagerh.) Born. & Flah.

Tarawa: 18816.

Microcoleus chthonoplastes (Mert.) Zanard.

Marakei: 18795, 18797; Tarawa: 18883.

Schizothrix calcicola (Ag.) Gom.

Nonouti: [illegible] (epiphytic on green algae); Marakei: 18795, 18797, 18807A (epiphytic on Enteromorpha); Tarawa: 18816, 18871, 18883, 18884.

This species was present in most of the collections sent to Dr. Drouet. Drouet says that the marine ecophenes (ecological growth-forms) of Schizothrix calcicola (Ag.) Gom. are such familiar "species" as Plectonema terebrans, Phormidium crosbyanum, and [illegible] rivulariarum. Dr. C. E. Palmer has found a virus which attacks all ecophenes which Drouet has indicated as S. calcicola in various culture collections.

Symploca hydnoides Kütz.

Marakei: 18793, 18797.

CHLOROPHYTA

Acetabularia mobii Solms-Laubach, 1895: 30, pl. 4 (fig. 1); Egerod, 1952: 411, fig. 23i.

Marakei: 18909 (fertile).

Thalli about 5 mm high, having 15-17 rays adhering to each other, with approximately 25-35 spherical cysts in each ray.

<u>Boodlea composita</u> (Harvey) Brand, 1904: 187; Egerod, 1952: 362, fig. 6a and pl. 32a.

<u>Marakei</u>: 18773; <u>Tarawa</u>: 18862.
Both collections forming dense spongy mats intermixed with <u>Hypnea</u>.

<u>Caulerpa racemosa</u> var. <u>macrophysa</u> (Kütz.) Taylor, 1928: 101, pl. 12 (fig. 3), pl. 13 (fig. 9); Eubank, 1946: 420, fig. 2n.

<u>Tarawa</u>: 18804, 18811, 18823, 18826, 18837, 18859, 18860, 18879.

<u>Caulerpa racemosa</u> var. <u>peltata</u> (Lamx.) Eubank, 1946: 421, figs. 2r-s.

<u>Tarawa</u>: 18839.

<u>Caulerpa racemosa</u> var. <u>turbinata</u> (J. Ag.) Eubank, 1946: 420, figs. 20p-q.

<u>Tarawa</u>: 18822, 18838, 18864.

<u>Caulerpa serrulata</u> var. <u>typica</u> f. <u>lata</u> (Weber-van Boose) Tseng, 1936: 178, pl. 1; Eubank, 1946: 418, fig. 2h.

<u>Marakei</u>: 18783; Tarawa: 18810.

<u>Caulerpa serrulata</u> var. <u>typica</u> f. <u>angusta</u> (Weber-van Boose) Eubank, 1946: 418, fig. 2j.

<u>Tarawa</u>: 18803, 18809A, 18835, 18850.

<u>Caulerpa sertularioides</u> (Gmel.) Howe, 1905b: 576; Dawson, 1956: 38, fig. 22.

<u>Tarawa</u>: 18802, 18806, 18820, 18827, 18853.

<u>Caulerpa urvilliana</u> Montagne, 1845: 21; Dawson, 1956: 37, fig. 21.

<u>Marakei</u>: 18788, 18799.
Both collections consisting of small thalli which were identified by Dr. William J. Gilbert.

<u>Chlorodesmis hildebrandtii</u> A. & E. S. Gepp, 1911: 16, 137, figs. 74, 75; Egerod, 1952: 377, fig. 9b and pl. 34a; Dawson, 1954: 394, fig. 11f.

<u>Tarawa</u>: 18821.
Filaments about 20 mm in length and 80 μ in width having a distinct bead-like swelling above each constriction. This collection resembles Egerod's illustration cited above which shows filaments constricted at frequent intervals, as opposed to Dawson's illustration which has fewer constrictions.

<u>Cladophora repens</u> (J. Ag.) Harvey, 1958: 236; Taylor, 1960: 82.

<u>Marakei</u>: 18942.
Small dichotomously branched filaments about 1 cm tall which seem to fit Taylor's description.

Cladophora sp.

Nonouti: 18890.
Filaments matted forming a small brown clump about 1 cm high.

Codium edule Silva in Egerod, 1952: 392, fig. 18a-c and pl. 35.

Tarawa: 18857.
Thalli repent with the branches adhering to each other and with numerous hairs projecting from the utricles.

Codium reediae Silva in Egerod, 1952: 379, fig. 17 and pl. 36.

Tarawa: 18840.
Thallus 9 cm tall with dichotomous and irregular branches not adhering to each other. The upper portion of the thallus is slightly compressed and numerous hairs can be seen upon macroscopic examination. The utricles are pyriform to truncate in shape, often 532 µ in length and 226 µ in width.

Dictyosphaeria cavernosa (Forsk.) Boergesen, 1932: 2, pl. 1 (fig. 1); Egerod, 1952: 350, fig. 1e-g.

Nonouti: 18889.
Clump approximately 2.5 cm broad comprised of one layer of cells, which lack spine-like processes on the interior surfaces of their walls. Segments polygonal, 700 µ in diameter with hapteroid cells present as in fig. 1f-g, of Egerod's paper.

It is surprising that Dictyosphaeria versluysii Weber-van Bosse was not found among these collections.

Enteromorpha intestinalis (L.) Link, 1820: 5; Dawson, 1954: 383, fig. 6c.

Tarawa: 18828, 18871.
Filaments about 3 cm tall covering a small piece of coral.

Enteromorpha sp.

Tamana: 18948.
This collection consists of small immature filaments covering a piece of coral.

Halimeda gracilis Harvey, ex J. Ag., 1887: 82; Hillis, 1959: 356, pl. 2 (fig. 4), pl. 5 (fig. 7), pl. 6 (fig. 9), pl. 7 (fig. 2), pl. 10.

Nukunau: 18892.
No distinct holdfast visible. Segments cylindrical in shape toward the base, with tear-shaped segments in the apical portions of the thalli.

<u>Halimeda incrassata</u> (Ellis) Lamouroux, 1812: 186; Hillis, 1959: 365, pl. 4 (figs. 1-2), pl. 5 (fig. 21), pl. 6 (figs. 21-24), pl. 12.

<u>Abemama</u>: 18898; <u>Tarawa</u>: 18801, 18817.

<u>Halimeda opuntia</u> (L.) Lamx., 1812: 186; Hillis, 1959: 359, pl. 2 (figs. 7-8), pl. 5 (figs. 3-4), pl. 6 (fig. 6), pl. 7 (fig. 3), pl. 10.

<u>Marakei</u>: 18771, 18790, 18907.
This species makes up the bulk of the algae collected from Marakei.

<u>Ulva lactuca</u> L., 1753: 1163; Dawson, 1954: 383, fig. 4.

<u>Tarawa</u>: 18833, 18843, 18854.
Most of these collections are mere fragments and at first glance look like small specimens of <u>Ulva fasciata</u> Delille. Upon microscopic examination of cross-sections, the cells seem to be relatively uniform in size and slightly taller than wide. In surface view the cells are polygonal and compact. These specimens fit the description of this entity in Gilbert's field manual.

<u>Valonia aegagropila</u> C. Ag., 1822: 429; Egerod, 1952: 348, pl. 29b.

<u>Tarawa</u>: 18844.
Vesicles 4-6 cm long and 1-2 cm wide forming a dense cushion in which both <u>Hypnea</u> and <u>Jania</u> are intermixed.

PHAEOPHYTA

<u>Dictyota crenulata</u> J. Ag., 1847: 7, 94.

<u>Marakei</u>: 18919; <u>Tarawa</u>: 18880A.
All collections are fragments about 2 cm high with the characteristic proliferations on only a few portions of the edges.

<u>Dictyota friabilis</u> Setchell, 1926: 91, pl. 13 (figs. 4-7), pl. 20 (fig. 1).

<u>Marakei</u>: 18785, 18792, 18800, 18906, 18943; <u>Nukunau</u>: 18894; <u>Tamana</u>: 18952; <u>Tarawa</u>: 18836, 18858, 18880B.
This species of <u>Dictyota</u> occurs throughout the Pacific area growing either as an epiphyte on other algae or on coral or basalt rocks. It usually grows in clumps but can be found growing as individual thalli as seen in these collections from the Gilbert Islands.

<u>Ectocarpus</u> sp.

<u>Marakei</u>: 18777; <u>Tarawa</u>: 18878B.
These collections are of but a few filments each, The filaments of 18777 were found growing on a piece of cord, while 18878B was found epiphytic on <u>Padina</u>. These specimens, both only about one millimeter tall, have sessile plurilocular organs up to 50 μ long and 20 μ wide,

which are slender and generally oblong in shape. The filaments are narrow about 20 μ wide and the cells are almost square in shape at the intercalary region. These filaments are too minute to be E. indicus Sonder while the plurilocular organs are not pyriform as in E. padinae (Buffham) Savageau.

Padina sp.

Tarawa: 18807, 18813, 18878A.
These collections are of fragments two cells thick throughout and producing oogonia.

Turbinaria ornata (Turner) J. Ag., 1848: 266; Dawson, 1954: 405, fig. 21.

Abemama: 18895.
Typical of the species as often collected in Hawaii.

RHODOPHYTA

Acanthophora spicifera (Vahl) Boergesen, 1910: 201, figs. 18, 19.

Tarawa: 18825, 18831, 18865, 18868, 18876.
All collections shrubby about 4-7 cm tall with Jania as the predominant epiphyte.

Ceramium fimbriatum Setchell & Gardner, 1924: 777, pl. 26 (figs. 43-44); Dawson, 1954: 446, fig. 55a.

Marakei: 18779.
Thalli about 4 mm high with distinctly bulbous hairs protruding from the nodes.

Chondria repens Boergesen, 1920: 300, fig. 40.

Nukunau: 18893.
A small mass of entangled thalli, with the largest thallus about 1 cm long. The habit of this alga resembles Boergesen's 1920 description and illustration of his species in all but one point. The tips of the branches of the Nukunau specimen are much more rounded than truncated.

Chondrococcus hornemanni (Mert.) Schmitz, 1895: 170.

Marakei: 18912.
This small piece of a thallus probably belongs to this species.

Falkenbergia hillebrandii (Bornet) Falkenberg = sporophyte generation of Asparagopsis taxiformis (Delille) Collins & Hervey; Feldmann & Feldmann, 1942: 89; Dawson, 1954: 414, fig. 25L; Taylor, 1960: 571, pl. 72 (fig. 8).

Marakei: 18776.
Thalli about 1.5 cm long and 30 μ wide with the three pericentral cells about 1.3 times as long than wide. Although both Dawson and Taylor

cited above have illustrated this species, Dawson's illustration is much more representative of the Marakei specimen.

Gelidiopsis intricata (Ag.) Vickers, 1905: 61; Dawson, 1954: 423, figs. 34a-d.

Tarawa: 18855.
Thalli cylindrical about 2-3 cm long bearing terminal stichidia. Rhizoids and apical cells absent from these thalli.

Gelidiopsis sp.

Tarawa: 18852, 18866.
Very similar to Gelidiopsis intricata (Ag.) Vickers except that the thalli are intertangled with each other.

Gelidium pulchellum (Turn.) Kütz. in Feldmann & Hamel, 1936: 119, fig. 23 and pl. 1 (figs. 2, 3); Dawson, 1954: 421, fig. 32b.

Tarawa: 18873.
Thallus about 2 cm in height radiating from a common point of attachment.

Gelidium pusillum (Stackh.) Le Jolis, 1864: 139; Dawson, 1954: 420, fig. 31a-c.

Marakei: 18778, 18908, 18946; Tarawa: 18815B, 18829, 18845.
Most of the collections are of immature forms but seem to fit Dawson's illustration.

Hypnea cervicornis J. Ag., 1852: 451; Dawson, 1954: 435, fig. 46d.

Tarawa: 18877.
The short branches of this specimen are not outstandingly cornuate or antler-like in shape as they are in Tanaka's illustration (1941, fig. 13c) but seem to be more similar to Dawson's illustration.

Hypnea esperi Bory, 1829: 157; Dawson, 1954: 436, fig. 46h-j.

Marakei: 18809B, 18874, 18885.
Long thalli with numerous short branches on the main axis.

Hypnea nidulans Setchell, 1924: 161, fig. 30; Tanaka, 1941: 246, fig. 18.

Marakei: 18772, 18784, 18791, 18798A, 18927, 18936, 18941; Tarawa: 18814, 18818, 18841, 18851, 18875.
Thalli compressed, about 2 cm high, and with pointed short branches similar to Setchell's illustration.

Hypnea valentiae (Turn.) Montagne, 1840a: 161, Dawson, 1954: 436, fig. 46L, 47.

Tarawa: 18812, 18867.
Forming thalli about 3 cm long.

Hypnea sp.

Abemmama: 18896; Marakei: 18922; Tarawa: 18832.

Forming a very compact mass of thalli up to 2 cm high with branches about 1 cm long.

Jania adhaerens Lamx., 1816: 270; Boergesen, 1917: 195, fig. 184, 185, 187.

Tarawa: 18856.

Forming a compact mass of thalli and sand particles.

Jania capillacea Harvey, 1853: 84; Boergesen, 1917: 198, fig. 188.

Abemmama: 18903; Marakei: 18775, 18786, 18789, 18794, 18905, 18938, 18940; Tarawa: 18830, 18842, 18861, 18882, 18886.

Forming a compact mass of thalli and sand particles intermixed, with individual thallus about 77 μ in diameter.

Jania tenella Kützing, 1858: 41, pl. 85 (fig. 2); Dawson, 1956: 49, fig. 43.

Marakei: 18930.

Collection consisting of but a few small thalli.

Jania ungulata Yendo, 1902: 26, pl. 3 (figs. 7-9), pl. 7 (fig. 8).

Tarawa: 18824.

Small compact clumps consisting of thalli and sand particles.

Laurencia obtusa (Huds.) Lamour., 1813: 130; Taylor, 1960: 626.

Marakei: 18787, 18926; Tarawa: 18819.

Thalli forming clumps, cells cylindrical in cross-section with the larger cells in center of thalli about 66 μ in diameter and those in the cortex about 27 μ.

Laurencia okamurai Yamada, 1931: [illegible], pl. 5 (fig. b), text figs. F, G; Taylor, 1950: 144; Dawson, 1956: 60, fig. 66.

Tarawa: 18869, 18881.

The surface cells which project at the apex of the branches are very conspicuous.

Laurencia paniculata (Ag.) J. Ag., 1863: 753; Dawson, 1954: 45[illegible], fig. 61c-d.

Abemmama: 18902.

Thalli slightly compressed with cells cylindrical in cross-section.

Lophosiphonia obscura (Ag.) Falkenberg, 1901: 500; Dawson, 1954: 451, fig. 58d-e.

Abemmama: 18900.

Main thalli prostrate with rhizoids present along the basal side.

<u>Polysiphonia</u> <u>coacta</u> Tseng, 1944b: 71, pl. 2; Dawson, 1954: 456, fig. 60g-h.

<u>Marakei</u>: 18774, 18782, 18921.
Thalli about 104 μ wide at the widest and cortical cells shorter than broad.

<u>Polysiphonia</u> <u>fragilis</u> Suringer, 1870: 37, pl. 25B (figs. 1-4); Dawson, 1954: 452, fig. 60a-b.

<u>Abemmama</u>: 18897; <u>Marakei</u>: 18780, 18937.
Intermixed with blue-green algae. These thalli seem to agree with Dawson's discussion and illustration.

<u>Polysiphonia</u> <u>subtilissima</u> Montagne, 1840b: 199; Tseng, 1944b: 70, pl. 1.

<u>Marakei</u>: 18911.
Growing as brown tufts about 5 mm high on coral pieces.

<u>Polysiphonia</u> <u>tongatensis</u> Harvey <u>in</u> Kuetzing, 1864: 14, pl. 41; Dawson, 1954: 454, fig. 60d-e.

<u>Tarawa</u>: 18805, 18815A.
Tetrasporic thalli about 1-2 cm tall.

<u>Tolypiocladia</u> <u>calodictyon</u> (Harv.) Silva, 1952: 308, Dawson, 1956: 58, fig. 62.

<u>Tarawa</u>: 18870.
Thalli intermixed with sand grains forming one intertangled mass. This specimen is well representative of Dawson's illustration.

<u>Wurdemannia</u> <u>miniata</u> (Lmk. & DC) Feldmann & Hamel, 1934: 544, figs. 9-11; Dawson, 1954: 424, fig. 35.

<u>Tarawa</u>: 18808.
Thalli about 1-2 cm long with anastomoses present as seen in Dawson's illustration.

<u>Acknowledgment</u>

The writer is grateful to Drs. Maxwell S. Doty and Albert H. Banner of the University of Hawaii for their support which made this work possible. He is also indebted to Dr. Francis Drouet of the Academy of Natural Sciences of Philadelphia who so unselfishly found time to provide the list of identifications of blue-green algae; to Mrs. Jane Cooper of the Department of Cooperative Society, Suva, Fiji, who made the collections including the valuable field notes; to Dr. William J. Gilbert who helped the writer identify some of the green algae; to Mr. Richard Buggeln, Miss Ernesta Galutira, Mr. Jan Newhouse, and Mr. Gavino Trono, Jr., all connected with the Botany Department, University of Hawaii, who gave at one time or another helpful advice in the identification of certain species of algae; and to Dr. Llewellya Hillis Colinvaux of the Department of Biology, Yale University, who verified and at times changed the writer's determinations of the species within the genus <u>Halimeda</u>.

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ATOLL RESEARCH BULLETIN

No. 106

New records of Halimeda and Udotea for the Pacific area

by

Edwin T. Moul

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New records of Halimeda and Udotea

for the Pacific area

by

Edwin T. Moul[1]

The collections of Halimeda and Udotea reported here constitute new records for the Pacific area. Knowledge of the distribution of these genera for the Pacific Ocean is far from complete, so the publication of these records will help to fill the gaps.

Time for the study was made possible through the aid of a Faculty Fellowship granted by the Research Council of Rutgers-The State University. The facilities and library of the Marine Biological Laboratory at Woods Hole, Massachusetts were made available through the courtesy of the Laboratory Management.

The nomenclature used is that of the monograph by Hillis (1959). The collections reported here were made by the following people:

J. T. Conover	1945-46	Guam, Saipan, Okinawa
Leonard Horwitz	1951	Arno, Marshall Islands
F. R. Fosberg	1951-52	Northern Marshall Islands
Maxwell Doty	1952	Raroia, Tuamotu Archipelago
	1953	Johnston Island, and Philippines
W. J. Newhouse	1954	Kapingamarangi, Caroline Islands
E. J. Kuenzler	1956	Okinawa

Specimens have been distributed to the following herbaria: University of Hawaii, Honolulu; United States National Herbarium, Washington, D. C.; Chrysler Herbarium, Rutgers-The State University, New Brunswick, N. J.; and University of California Herbarium, Berkeley. Some duplicates have been sent to New York Botanical Garden, Bronx, N. Y.; W. R. Taylor, University of Michigan, Ann Arbor, and L. W. Hillis at Yale University.

Arno Atoll, Marshall Islands

(Pacific Science Board Expedition - 1951)

This collection, including 9 species of Halimeda, was made by Leonard Horwitz, whose collection numbers identify the specimens.

[1] Botany Department, Rutgers-The State University of New Jersey.

Halimeda lacunalis Taylor

On lagoon reef flat and on the downward slope to a depth of 30 feet.
Ine Village: MD 9084, 15 July.

Halimeda lacunalis Taylor f. lacunalis

On upper and lower surfaces of rock in 20-30 feet of water, downward slope beyond lagoon reef ridge.
Ine Village: MD 9076B, MD 9076C, 15 July.

Halimeda discoidea Decaisne

Growing on the drop-off of lagoon reef, not deeper than 10 feet at high tide. Shaded by overhanging rocks and corals.
Ine Village: 9720B, 27 Aug.

Halimeda taenicola Taylor

On lagoon reef flat and the downward slope of lagoon reef. Shaded by coral or rocks in some cases.
Ine Village: 9072C, 9072D, 10 July; 9577, 9599, 17 Aug.; 9675, 9676, 9683, 22 Aug.

Halimeda opuntia (L.) Lam. v. opuntia

Hillis (1959) has placed the typical species and its many integrated forms in v. opuntia. It was pointed out by Moul (1959) that frequently one described growth form suddenly changed to another on the same plant, therefore the placing of these forms here seems logical.

Found on lagoon flat and downward slope beyond lagoon reef ridge to 30 feet. Also on ocean reef flat and in drop off on ocean side to 15 feet. In crannies and under rocks and corals, frequently shaded. Material collected from the ocean reef, individual segments very small, 3-4 mm wide by 4-5 mm long.
Ine Island: 9072A, 9072B, 9072F, 10 July; 9084D, 15 July; 9161, 27 July; 9162, not dated; 9559, 6 Aug.; 9471, 10 Aug.; 9525, 9526, 9528, 9529, 9530, 14 Aug.; 9546, 9547, 9549, 15 Aug.; 9577A, 17 Aug.; 9548, 9674, 22 Aug.; 9720C, 27 Aug.

At the inshore end of a long chasm, ocean reef.
Kabinlak Island: 9094, 20 July.

Halimeda fragilis Taylor

On lagoon reef drop off.
Ine Village: 9673, 22 Aug.

Halimeda micronesica Yamada

Beyond and below the ocean reef ridge, on rock mass in 30 feet of water.
Eduk Island: 9034, 7 July.

Downward slope of lagoon reef ridge in 20-30 feet of water.
Ine Village: 9076A, MD 9084B, MD 9084G, 15 July.

Sheltered area at low water mark in a chasm of the ocean reef ridge.
Kabinlak Island: 9093, 20 July.

Halimeda incrassata (Ellis) Lam.

All in 20-30 feet of water on downward slope, beyond lagoon reef ridge.
Ine Village: MD 9084C, MD 9084E, MD 9084F, 15 Aug.

Halimeda cylindracea Decaisne

On lagoon reef flat or downward slope to a depth of 30 feet. One collection from over the edge of the reef on the ocean side of the island.
Ine Village: 9072G, 10 July; 9084H, 15 July; 9161B, 27 July; 9675B, 22 Aug.

Halimeda stuposa Taylor

On lagoon reef flat.
Ine Village: 9043, 9072E, 10 July.

Sandy floor of lagoon reef.
Matol-en Islet: 9492, 12 Aug.

Northern Marshall Islands 1951-1952

The algae recorded here were collected on the United States Geological Survey Expedition "Project Atoll", 1951-1952, which visited the Northern Marshall Islands. The narration of the trip and a description of the atolls visited have been written by Fosberg (1955) who made the algal collections.

Halimeda lacunalis Taylor f. laxa (Taylor) Hillis

On the southwest reef, in cavities in the upper surface of coral clumps on the deeper part of the reef flat. Plants truncated at the coral surface.
Bikar Atoll: Bikar Islet, 34554A, 7 Aug. 1952.

Halimeda taenicola Taylor

On the deepest part of the reef flat, on gravel covered by a thin layer of sand.
Ailuk Atoll: Ailuk Islet, 33919, 26 Dec. 1951.

On the seaward reef flat, near the outer edge, just below low tide level.
Kwajalein Atoll: Lojjaviok Islet, 34113, 15 Jan. 1951.

In small holes in the surface of the leeward reef in the lagoon, just exposed at low tide.
Pokak Atoll: Sibylla Islet, 34537, 26 July 1952.

First two collections from cavities in the deeper part of the reef flat; third in a moat on the outer side of the ridge, exposed to wave action.
Bikar Atoll: Bikar Islet, 34554B, 34560, 7 Aug. 1952.
Jaliklik Islet, 34585, 9 Aug. 1952.

Halimeda opuntia (L.) Lam. v. opuntia

In crevices between rocks in the deepest part of the channel, at extreme low tide mark, passage east of Enemanet Islet.
Lae Atoll: Enemanet Islet, 34085, 10 Jan. 1952.

On the sandy and rocky bottom of the reef flat and between coral clumps, below low tide level.
Ujae Atoll: Bock Islet, 34349, 19 Feb. 1952.
Wojia Islet, 34389A, 4 March 1952.

A bleached specimen was collected in the wash along the beach.
Wotho Atoll: Eneobnak Islet, 34443, 20 March 1952.

In small holes on the leeward reef in the lagoon, just exposed at low tide.
Pokak Atoll: Sibylla Islet, 34536, 26 July 1952.

Halimeda micronesica Yamada

From small holes in the leeward reef in the lagoon, just exposed at low tide, with H. opuntia and H. taenicola.
Pokak Atoll: Sibylla Islet, 34535, 26 July 1952.

Halimeda stuposa Taylor

On the bottom of the lagoon at the end of the South passage.
Likiep Atoll: Lado Islet, 33837, 15 Dec. 1951.

Common on the sandy bottom of the lagoon, below high tide level. The holdfast was deeply embedded in the sand of the reef flat.
Ujelang Atoll: Ujelang Islet, 34190, 4 Feb. 1952.

Common on the sandy bottom at extreme low tide level.
Wotho Atoll: Wotho Islet, 34224, 12 Feb. 1952.

Along the lagoon beach with H. opuntia.
Ujae Atoll: Wojia Islet, 34389B, 4 March 1952.

Udotea argentea Zanardini f. typica A. & E. S. Gepp

Embedded in coral sand and gravel at the bottom of the lagoon.
Likiep Atoll: Lado Islet, 33838, 15 Dec. 1951.

On the reef flat with Halimeda taenicola; the substrate, sand covered gravel or Porites coral.
Ailuk Atoll: Ailuk Islet, 33920, 26 Dec. 1951; 33948, 33949, 33950, 33951, 27 Dec. 1951.

Udotea indica A. & E. S. Gepp

On rock floor of the reef flat near the outer edge.
Ailuk Atoll: Ailuk Islet, 33982, 28 Dec. 1951.

Raroia (Barclay de Tolley) Atoll
Tuamotu Archipelago

(Pacific Science Board Expedition - 1952)

Only 2 species of Halimeda were in the collection of Maxwell Doty and W. J. Newhouse from Raroia Atoll. Doty reports (1954) that no living Halimeda were dredged from the bottom of the lagoon, but the sides of reef patches were clothed with this genus and Caulerpa.

Halimeda discoidea Decaisne

Large well developed plants growing on coral patches in 10 feet of water. Plants from 12 to 30 cm tall.
Jakeke and Obreroa Islets: 11159, 9 July; 11498, 2 Aug.; 11636, 8 Aug.

All small, depauperate plants, growing in holes on inside edge of lagoon reef. One in hole of boring urchin.
Kukina and Ngarumaoa Islets: 11231, 18 June; 11804, 16 Aug.; 12154, 3 Sept.

Halimeda taenicola Taylor

Outer reef puka, incurrent area in overgrown surge channel.
12162, 3 Sept.

Philippine Islands

Collected by Maxwell S. Doty on the east shore of Paniquian Island, Puerto Galero, Mindoro.

Halimeda opuntia (L.) Lam. v. opuntia

Plants with very small segments.
12345, 2 Dec. 1953.

Halimeda macroloba Decaisne

12346, 2 Dec. 1953.

Johnston Island

Collected by Maxwell S. Doty, north of northeast end of seaplane runway.

Halimeda tuna (Ellis and Solander) Lam.

10993, 4 Dec. 1953.

Hawaiian Islands

Collected by Maxwell S. Doty and W. J. Newhouse at Kailua beach on Oahu.

Halimeda gracilis Harvey ex J. Agardh

Washed onto the beach. Plants straggling and decumbent.
12423, 13 March 1954.

Kapingamarangi Atoll, Caroline Islands

(Pacific Science Board Expedition - 1954)

This collection of 9 species, was made by W. J. Newhouse, whose collection numbers identify the specimens.

Halimeda lacunalis Taylor f. lacunalis

In lagoon of the atoll, at 2-10 feet; all on coral with one exception, this growing to 35 cm long, at 2 feet depth, in a rusted LCM.
1103, 8 July; 1422, 3 Aug.; 1512B, 7 Aug.; 1613, 14 Aug.

Halimeda lacunalis Taylor f. lata (Taylor) Hillis

On the sea reef opposite Touhou, 5 meters from the seaward margin.
1022, 28 June.

Halimeda discoidea Decaisne

In 6 feet water at low tide on branching coral, lagoon reef.
1515, 7 Aug.

In 10 feet water in a cavern of a micro-atoll.
1529, 7 Aug.

Halimeda taenicola Taylor

The macroscopic appearance of this taxon varies considerably, but the arrangement of nodal filaments and the presence of three layers of utricles with the third layer the largest in diameter, is common to all of the specimens represented.

On the seaward reef, over the edge in 10 feet of water, in the channels of the reef and on reef flat in Amphiroa zone. Also in lagoon, in shaded areas on coral mesas, micro-atolls and coral heads, from 2 to 10 feet of water.
1009, 24 June; 1036, 29 June; 1105, 1106, 1107, 8 July; 1223, 1224, 21 July; 1520, 7 Aug.; 1570, 9 Aug.; 1590, 12 Aug.

Halimeda opuntia (L.) Lam. v. opuntia

In the lagoon at low tide level to 10 feet. On seaward reef in the Amphiroa zone, plants with very small segments.
1008, 24 June; 1015, 25 June; 1024, 28 June; 1031, 1042, 29 June; 1100, 8 July; 1518, 7 Aug.; 1580, 1581, 11 Aug.; 1603, 1604, 1605, 12 Aug.

Halimeda opuntia (L.) Lam. v. hederacea (Barton) Hillis

This variety has larger segments and is very heavily calcified. Plants resembling these and placed in this variety were common on Onotoa, Gilbert Islands (Moul, 1959).

Mostly in the lagoon at 4-15 feet. Two specimens from western rim of atoll on lagoon side of seaward reef at 5 feet.
1017, 26 June; 1029, 29 June; 1237, 21 July; 1578, 11 Aug.; 1602, 12 Aug.; 1645, 19 Aug.

Halimeda fragilis Taylor

In lagoon at 2½-15 feet, most of them pendulous or under overhangs on corals or micro-atolls.
1030, 29 June; 1100B, 1102, 8 July; 1266, 22 July; 1519, 7 Aug.; 1556, 9 Aug.; 1579, 11 Aug.; 1591, 12 Aug.

Halimeda micronesica Yamada

In lagoon at 4-10 feet, on base of corals, coral mesas, or micro-atolls, frequently on shaded underside. Three specimens on seaward reef, on the margin and over the edge at 10 feet.
1007, 24 June; 1023, 28 June; 1035, 29 June; 1104, 8 July; 1225, 21 July; 1510, 1521, 7 Aug.; 1592, 1593, 12 Aug.

Halimeda incrassata (Ellis) Lam.

In lagoon, one plant at 15 feet, on base of branching coral; a second, small specimen at 4 feet with H. opuntia on a coral mesa.
1577, 11 Aug.; 1602B, 12 Aug.

Halimeda cylindracea Decaisne

On lagoon reef, to 15 feet, around bases of massive corals. In channels between islands at 2 feet. Plant 1034, collected on June 30th, covered with gametangia.
1028, 29 June; 1034, 30 June (gametangia); 1101, 8 July; 1528, 11 Aug.

Halimeda stuposa Taylor

In lagoon on sand flats; one plant from western rim of atoll. Usually in shallow water, but found to 6 feet. One plant only 7½ cm tall had a massive holdfast, 10½ cm long by 5½ cm broad.
1016, 26 July; 1301, 27 July; 1400, 3 Aug.

Guam

The four species of Halimeda reported here for Guam were collected by J. T. Conover in 1945.

Halimeda lacunalis Taylor

On sandy bottom near shore and on coral blocks in shallow water. Abundant.
Agat Bay: 50 yards east of Neye Island. 720, 8 April.

Halimeda opuntia (L.) Lam. v. opuntia

On sandy bottom near shore and on coral shelf, midreef.
Asan point: 3002, 14 Jan.; 3001 (760), 2 Feb.; 727, 21 March.

Halimeda cylindracea Decaisne

In shallow water, midreef on sandy bottom.
Agat Bay: Near Neye Island. 706, 8 April.

Halimeda macroloba Decaisne

In shallow water, sandy bottom, on coral fringe reef. Plant 401, collected on Feb. 5th, was covered with gametangia.
Tumon Bay: Near Amantes Point. 3000, 3 Jan.; 401 (gametangia), 5 Feb.
Pago Bay: 741, 16 Feb.

Saipan

One specimen of Halimeda from Saipan was included in J. T. Conover's material for 1945.

Halimeda macroloba Decaisne

Abundant in shallow water. Sandy bottom in basins between coral heads, within inner reef barrier and on open coral flats seaward one mile on the 3 mile reef area.
Tanapag Harbor: 757, 22 April.

Okinawa

The collections reported were made by J. T. Conover in 1945-46, and E. J. Kuenzler in 1956.

Halimeda discoidea Decaisne

Very young, fragmentary plants. Conover 3004, 20 Aug. 1945.

Halimeda opuntia (L.) Lam. v. opuntia

Conover 3003, 20 Aug. 1945.

Halimeda opuntia (L.) Lam. v. hederacea (Barton) Hillis

In tide pool on coral shelf, ¼ mile off shore.
Onno Peninsula: Conver 781, 10 July 1945.

Halimeda incrassata (Ellis) Lam.

On sandy bottom in 4 feet of water, to 200 yards seaward.
Kanna Ko: Conover 790, 20 Sept. 1945.

On coral flats, shallow water.
Nago: Conover 850, 19 March 1946.

Sand and coral intertidal zone.
Bolo Point: Kuenzler 186, 187, 188, 29 Aug. 1956.

Halimeda simulans Howe

On coral sill of shore reef.
Yonanaru: Conover 796, 8 Oct. 1945.

On gently sloping sand and coral beach.
Bolo Point: Kuenzler, 148, 149, 150, 185, 19 Aug. 1956;
198, 199, 30 Aug. 1956.

In 4-10 feet water, sandy area between scattered coral rocks.
Lolly Beach: 121, 15 July 1956.

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Place names on Nukuoro Atoll

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Place names on Nukuoro Atoll

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Vern Carroll[1]

I. Island names and atoll building in Nukuoro

Nukuoro Atoll (Ponape District, Trust Territory of the Pacific Islands) is a nearly circular atoll with a deep central lagoon and a nearly unbroken fringing reef averaging one third of a mile in width. From the Northwest in a clockwise direction around to the Southwest, range a series of modu[2], or small islands (see map). At low tide it is usually possible to walk from one modu to another without getting wet; at high tide, the modu are separated by narrow watercourses. When the tide is coming in or out, these are swiftly moving.

Etymologically modu means something 'terminated'. In this case it is the land above the high water level, on which grows a typical atoll vegetation, which is broken by sand, coral and sometimes water.

The present disposition of the forty-six modu in Nukuoro atoll is thought by the inhabitants to have persisted for a long time: people are aware of only a few minor changes in the atoll topography. Careful research, however, has uncovered evidence of greater change than is popularly recognized. There is also considerable evidence that some of these changes represent accretions to the atoll in the form of whole islands built by the hand of man. Since atoll-building is not generally thought of as comprising part of the technical resources available to the inhabitants of insular Oceania, this evidence is thought to be significant. The mode of research into this matter which we have employed is also thought to represent a useful method which might produce comparable results elsewhere.

Our first indication of the existence of extra names for modu, in addition to those names which we had collected for the modu now visible, came with our recording of a mou, or mnemonic (see below), for modu which was difficult to relate to the present disposition of the atoll. Clearly the mou listed the modu names in order — beginning with the modu in the extreme Southwest of the atoll and proceeding in a counter-clockwise direction to the terminal modu in the Northwest. Thus it was possible to use those names for contemporary modu which coincided with names in the mou as reference points from which to zero-in on the confusing disparities. In some cases, a synonym was found for a current name which coincided with the mou name; in some cases there were several names where a single modu now exists; in other cases a modu is now present, although it is not mentioned in the mou.

1/ University of Chicago.

2/ Spelling in the accepted Nukuoro orthography of the well-known Polynesian word motu.

Where it appeared that a single modu had been formed from smaller ones, geological reconnaissance usually demonstrated the former existence of channels in the form of wide sandy swaths extending continuously below the topsoil from the lagoon side of the atoll to the sea side. Often place names for parts of the island (of which there are a very great number—a matter to be covered in a subsequent paper) coincided with the relevant modu names in the mou. A cadastral survey also showed that these former channels were invariably plot boundaries—contrasting in their irregularity with normal straight land boundaries. Each of the older atoll inhabitants was able to cite one or two cases of such processes; eventually every suspected case was confirmed in one or more traditional stories collected from these people.

It might seem strange that a "mnemonic" for the names of the modu in an atoll could have so long resisted being changed to accord with the contemporary facts. But this appears to have been precisely the case. These mou, of which there are a considerable number—covering the names for different kinds of sea life, plants, varieties of pandanus, names of priests, birth order of people born into the community during a certain span of time, etc.—are considered somewhat esoteric; one seeks out one of the 'old people' who knows such things usually only late in one's own lifetime—to equip oneself with the knowledge to assume one's role as one of the 'old people'. The mou gives only one or two syllables from each of the complete names which it incorporates, so it is not immediately apparent to the incurious that a contradiction exists between the abbreviated name and that thing it represents. Few people who have learned these mou make an effort to relate them to the entities they are supposed to represent. It is, after all, only the knowledge of the mou which counts—not its implications. Thus it is really not, properly speaking, a 'mnemonic'; it is a token for the kind of systematic knowledge which is prized as an emblem of status, without much contributing to that knowledge. Where such devices occur, they might be exploited in the way in which we have done here to provide some historical perspective on geography. The fact that they do not change with the times is for the historian a blessing. The fieldworker is warned, however, that some individuals do compare their mou to the contemporary names, or compare their mou to those of other people—the mou thereby becoming corrupt through alteration. Only the collection of a large number of mou and traditional stories supplemented by on-site inspection can be expected to produce satisfying results.

For modu which appear on the map but not in the mou, we found that these either represented a division of one island into several following a severe storm--a fact which was handed down from one generation to the next as a matter of oral history—or had been "purposely left out of the mou because they were not natural islands but islands made by men". In general, the method of making a modu appears to have been the accumulation of hunks of loose coral relatively close to the lagoon side of a wide portion of reef, letting the sea wash up sandy fill, and then planting trees and shrubs in this soil to consolidate it (perhaps using vegetable matter from elsewhere to enrich the soil). An island made in this way became the exclusive property of the man or family that made it. One suspects that the process would take at least several generations.

To this day the islands which are claimed to have been recently built up in this way are owned by a single individual or family——in contrast to the overwhelming majority of modu, in which a great number of families have interests. This contrast is illuminated further by the suggestion that 'ownership' on this atoll derives ultimately from the person who made a piece of land productive. Before the advent of the copra trade, one suspects that a great deal of available land on other modu was not exploited——land closer to one's residence providing ample sustenance. Land on the main island (Nukuoro), which is used for building sites and the raising of coconuts for eating and drinking, and land in the six taro patches (two on the main island and four on nearby islands) has long been at a premium and is highly fractionated between the various families. Land in other modu is similarly divided ——most probably representing an earlier situation in which the present owner's ancestor brought a piece of it under cultivation for subsistance purposes, or cleared a house site [although houses are presently concentrated in a village on the main island, there was formerly considerable occupation of other modu, which in certain seasons provided a more convenient base from which to collect and dry the fish which were eaten at other times of the year when the fishing was poorer].

The affinity of native ideas about ownership with those about productive use is illustrated by a story that recounts a land dispute between a Nukuoro man and someone who had arrived not long before from another island. It is recounted that they decided the issue between them by each planting a tree, with the understanding that the one whose tree grew up strong would henceforth have undisputed title to the island. The interloper's tree flourished and his opponent quietly withdrew!

Having uncovered several cases of island building from the omission of names from the mnemonic, one began to suspect something similar in the case of several small islands, all of which are called Deahu. In contrast to the other modu, these have no distinctive name——being discriminated where necessary by adding the name of the current owner. Like the modu just discussed, all of them are owned by a single individual or family. On at least some of them there is evidence of the construction of seawalls and other techniques for maintaining the integrity of the small land mass. There is a possibility that these too are made by man, our inference here being principally philological. Other island names containing the morpheme ahu possibly reflect a similar state of affairs.

The etymology of deahu is somewhat obscure. De is one kind of 'article' like the English 'the'; dahu is the preparation made for one kind of fire——that in which sticks, or other combustible things are piled up in an orderly fashion. Ahu is not used in Nukuoro at the present time for a pile of stones, but in many other Polynesian languages, e.g. Tahitian, Hawaiian, it means just that. The argument here is at best tenuous, but it does at least suggest that island building on Nukuoro may have been a much more important factor in the present layout of the atoll than our few better-documented cases would lead us to suspect.

Several other modu have alternative names which include the root ahu. Here again we suspect atoll-building at some remote point in time. In addition, certain additional island names point to human or natural consolidation.

Augmentation of one's property at the expense of the sea proceeds to this day in many smaller ways, especially along the lagoon face of the main island. Property owners here have erected stone piers to hasten the accumulation of drifting sand; seawalls are built out a bit from the high water level and debris is thrown into any low damp area behind them to provide fill; only enough coral is removed from the reef on the lagoon side to provide a channel for canoes to their storage sheds at low tide, the rest being left there to prevent sand from washing away.

A practical feature of our observations here is the possibility which may still exist on many atolls for increasing the available land under cultivation. Where lagoon depth, fishing, rainfall, and other resources permit, atoll building under government sponsorship might produce extra land for an expanding population without good opportunities for migration. On comparatively well-endowed atolls, such as Nukuoro, such potentialities put the matter of "population pressure" in clearer perspective: presumably if the population were in fact "pressing" on available resources, they would be doing something about it.

Table I and accompanying notes present the substantiative detail which we have omitted in the above discussion.

Table I

Order	Present Name	Mou	Mou Name	Other Names and Notes
1. ***	Moduilalo	gele	Mogelegele-idaha	O, P
2. ***	Olomanga	olo	idem	I, O
3. ***	Deahua	#		(3 & 4 together called Lumodu)
4. ***	Moduilodo	gele	Mogelegele-ilodo	L, O
5. **	Gausema	gau	idem	M
6. **	Senugudai	nugu	idem	J; Senuku (= abbreviation)
7. *	Masabu	hili	Mohilignadua	B
8.	Masagumani-ingage	sagu	idem	
9. **		ahu	Ahua	C
		nau	-nau	C
	NUKUORO	mada	Madalam	C
		gina	-gina	C
		hidi	Dagahidihidi	C
		bua	Moduobua	C

Table I (cont.)

Order		Present Name	Mou	Mou Name	Other Names and Notes
10.	**	Dagamanga	dau	Daumaha	K; Taumaha (singular of daumaha)
11.		Ladi	dini	idem	(di + ni for completion of mou element)
12.		Demodu	modu	idem	
			nini	Ninidauana	D
13.	*	Haisisi	hai	idem	B; Deangimaiolo
			baga	Bakau	
14.	*	Ngaligi	ligi	idem	E; Bagau
15.		Sungaulohu	sunga		
			holu	maholu	F
16.	*	Tuila	tui	idem	
17.		Haduganae	hadu	idem	
18.		Balaiasi	bala	idem	
19.		Moduovega	vega	idem	
20.		Baonga	bao	idem	
21.	***	Ahuloloa	loa	idem	
			dini		
			lage		
			dule		
			lage		
			bo		
			guba		
22.		Moduodula			Moduosaualoualo, Ngana
23.	***	Ahuedolu			G
24.		Moduovae	vae	idem	
25.	***	Deahu	ahu	idem	H, N
26.	***	Deahu	ahu	idem	H
27.	***	Deahu			A, H
			ei		(indicates a pause between major groups of modu)
28.		Sabinimadogo	bini	idem	
29.		Modubodai	dai	idem	
30.		Moduidua	dua	idem	
31.	***	Ahuilodo	lodo	idem	
32.		Dahangahaino	hanga	idem	
33.		Dahangadabu	hanga	idem	
34.	***	Ahulegalega	lega	idem	
35.		Masagumani-ilalo	mani	idem	
36.		Niulegida	niu	idem	
37.	***	Ahulanui	#		
38.		Dolungahale	dolu	idem	
39.		Dalagivao	dala	idem	
40.		Moduia	ia	idem	
			deni		
			ua		

Table I (cont.)

Order		Present Name	Mou	Mou Name	Other Names and Notes
41.		Modunui			
42.		Namooilodoa	namo	idem	
43.	***	Hauosiga	siga	idem	Ahuesiga
44.		Gabinivele	vele	idem	
45.		Dalainamo	hau	Haungaobo	
46.	***	Deungagelegele	#		O

Key to columns in Table I

"Order" = serial position of the modu beginning at the Southwest extremity of the island chain and proceeding counterclockwise to the Northwest extremity [this is the local convention for the enumeration of the modu]. [see accompanying map]

Asterisks indicate the evidence for atoll building:

* indication of agglomeration of modu through natural or human agency
** present extent and productivity of modu appears to be the result of atoll building
*** probably owes its existence to human agency

"Present name" = name in most common use at the present time. These names, and all other Nukuoro words in this paper, are written in the standard phonemic orthography for Nukuoro. This orthography was developed by a former Chief; we have assisted only in codifying it and in helping to standardize certain usages, spelling of proper names, word division, and the like. One such usage—now locally accepted—which is reflected in these names, is the writing of all proper names as a single word with an initial capital letter, except where this obscures juncture between vowels. In the latter case, a hyphen separates the vowels which might otherwise be ellided [v. 8 & 35 above].

"Mou" - gives the elements of the mou in order [conventionally recited in lines of four elements each]. The rules of this (and all other) mou that enable one to associate the elements with names for modu are three in number: (1) each element consists of two syllables; (2) each element pertains to one modu; (3) the elements are in order—as outlined above for the enumeration of the modu.

"Mou name" - the name for the modu to which the mou element refers. These are all thought of as alternative—usually older—names for the modu. "Idem" in this column indicates that the present name and the mou name are identical.

"Other names" = alternative names for the modu, in addition to the mou name.

"Notes" - refers by letter, to the notes following.

Notes

N.B. Numbers following letters refer to modu, as enumerated above.

No gloss is provided below for ahu. This we have treated as best we can in the text.

- Islands thus marked are said to have been left out of the mou because "they are not natural islands but made by men". Since there is considerable evidence that the mou includes artificially made modu, this is taken to mean that the modu in question were constructed long after the earlier efforts reflected in the mou. A rough date could possibly be established for each of these cases through geological comparison of the consolidation of these modu with those undisputably much older.

A. 27 was formed from two ahu: Ahuidua + Ahuidai

B. Several contemporary modu names are said to be names for only one of the several modu from which it was formed: 7, 14, 13 (Haisisi said by some to be just part of Deangimaiolo). It is not of course possible to determine in these cases whether the joining of adjacent modu proceeded spontaneously or was effected with human assistance, except by detailed geological survey.

Several names in the mou are said to refer to once separated modu which are now joined together. In most of these cases, such names are now found as place names on the consolidate.

C. 9.
- a. mada = Madalama (mythological name of Nukuoro)
- b. -gina- joined Madalama, as represented in Madagina (another very old name for Nukuoro)
- c. Deahua and -nau- joined to form Ahunau and Ahunau joined Madagina. The Southeastern portion of Nukuoro has two place names which reflect this join: Debigi ('rocks put together') and Debai.
- d. Two separate modu, Dagahidihidi and Moduobua (each of which is a place name in the extreme Northeast portion of Nukuoro island), each joined the above agglomerate to form the present island of NUKUORO.

D. 13. Ninidauana is a place name on Haisisi.

E. 14. Ngaligi is thought by some to be a synonym for Bakau, but tradition records that it was originally an adjacent island.

F. 16. Maholu is a place on Tuila at present (southern portion). Tradition records that it was once a separate islet.

G. 23. Ahuedolu ('three ahu') is said to have been formed from Dinilage + Duleilage + Boguba, each of which was formed from two others. This construction leaves the status of island 22 in doubt.

Notes (cont.)

H. 25, 26, 27. These ahu, collectively called Denga-ahu ('the (pl.) ahu') are distinguished where necessary by adding 'belonging to [name of owner]'.

Place names on several _modu_ whose _mou_ name gives no clue to prior consolidation reflect some human intervention in its formation.

I. 2. Olomanga (etymologically, _olo_ 'place where the sand comes together' + _manga_ 'something branching') is divided into three main divisions (running seaward to lagoonward).

Deahuagelegele (gelegele = 'sand')
Deahuagasi (gasi = a kind of shell)
Deahuanau (nau = kind of tree—planted at the water's edge to consolidate soil against erosion by the sea)

J. 6. The side of this island toward the channel is called Debigi ('rocks put together').

K. 10. South side is called Deahunau [cf. note I].

A few _modu_ have disappeared or become smaller.

L. Between 4 and 5 Deahuaodeubi was washed away in a storm.

M. 5. Extension of this island to the channel (by its inhabitants) was subsequently washed away.

N. Between 25 and 26 one ahu (Ahu o Taohenga; later called Ahu o [illegible]aane) was washed away in a storm.

O. Those islands which contain gelegele ('sand') in their name are thought to have been originally sandbanks, which required considerable human effort to make into permanent and productive _modu_: 1, 2, 4, 46.

P. Occasionally a legend recounts the making of an island by a human being.

II. Directions on Nukuoro

Looked at on a map oriented North, the 46 islets (_modu_) of Nukuoro Atoll form a backwards "C". The chain of islands stretches from the Southwest, around in a counter-clockwise direction to the Northwest.

The Nukuoro perceive this in the reverse way. The southwestern terminus of the chain is _ngage_ (_nga_ makes a substantive of the following adjective; _age_ is not now used other than to indicate a direction on the atoll—in many other Polynesian languages, however, (e.g. Maori) it means 'front'). The northwestern terminus of the chain is _ngaiho_ (_nga_ + _iho_ 'back'). The traditional rhyme for enumerating the _modu_, the _mou_, begins at _ngage_ and ends at _ngaiho_.

From any place on the atoll one is 'going ngage' when one is going away from ngaiho, and vice-versa. In the unlikely event that one were proceeding afoot along the submerged reef which separates ngage and ngaiho, the same rule would apply: leaving ngage, one is going ngaiho, and vice-versa.

Thus it will be seen that directions on Nukuoro are relative, not absolute: one may be 'going ngage (or ngaiho)' and be proceeding along any possible compass bearing at the time. This is somewhat obscured in the minds of some of the younger and better-educated Nukuoro who, having been taught compass directions in school, want to construe ngage as 'South' and ngaiho as 'North', since this is the case on the island of Nukuoro on which the single village is established (and by far the area within which these terms are used most frequently). Since most travel to other modu is by canoe (in which case one would simply say that one were 'going to [name of modu]'), these individuals are not apt to use or hear these expressions enough to remind them that their usage by the majority contrasts with this modern usage. Another factor that tends to obscure the relativistic character of this usage is the fact that any travel towards the island of Nukuoro is called 'going hale' ('home'). Going away from ngaiho towards Nukuoro or away from ngage towards Nukuoro one does not have occasion to say that one is going ngaiho or ngage. Thus in everyday usage 'going ngage' is used only for foot travel from Nukuoro towards ngage and 'going ngaiho' from Nukuoro towards ngaiho; but most especially these terms are used for travel on the islet of Nukuoro.

Parallel to this directional terminology which refers to direction around the circumference of the circle formed by the atoll's islets, is a pair of terms, one of which refers inward toward the center of the circle, the other of which refers outward from the circumference. I dai ('on the water', i.e. 'lagoonward') contrasts with i dua ('on the back', i.e. 'seaward'). Here again there is a bit of confusion when these terms are made to apply to 'West' and 'East'—thinking of the absolute directions to which they correspond on the main island. Usage of these terms, however, is consistent: from any part of the atoll, i dai is toward the center of the lagoon and i dua is toward the open sea, irrespective of the absolute directions involved.

It will not be argued on this slender bit of philology that the orientation in native thought of Nukuoro Atoll towards the South indicates that its people originally came from there—although the people themselves and early ethnologists claim precisely this—but we would argue that spatial orientation, especially the matter of looking inward, away from the moana ('void', 'open sea') is reflected in their social organization. This matter, however, is more conveniently relegated to a subsequent paper.

NUKUORO ATOLL

VC

SKETCH MAP ADAPTED FROM H.O. 6042

III. The names of the islets on Nukuoro Atoll

In making maps, it is generally considered cheating to simply copy an older map. However, no such strictures seem to apply to place names. Cartographers are wont to perpetuate the most preposterous errors through inattention to this aspect of map-making.

There are several unfortunate results. Native peoples, now almost universally literate in their own language, are not infrequently offended when the names of their islands are incorrectly spelled. This is especially true where there is a standard official orthography to which the surveying party pays not the slightest heed, preferring to record place names impressionistically (and, inevitably, inconsistently). Would it be appropriate for a Dutch geographer to spell New York as 'Nieu Jook'?

In non-self-governing territories educators are making an effort to teach local people a respect for European standards of scholarly and scientific work. Maps are widely circulated in these territories. Errors in the maps themselves may escape notice for decades; but place names are immediately visible—and immediately judged.

The worst possible result of inaccurate geographic names is the confusion they engender. On Nukuoro, the people are inclined to believe that "the white man knows best." If the names on the maps are right, then the Nukuoro orthography, which has been the educational standard for over forty years, is wrong. In point of fact, the Nukuoro orthography conforms to the highest standards of linguistic science. The author, a trained linguist and anthropologist, was unable to improve on this orthography, which had been devised more than a generation ago by a local chief. The names on the maps, on the other hand, are most definitely wrong. Not only is the orthography in error, but islets are, in some cases, misnamed altogether.

The following is a definitve list of the present names for the islets of Nukuoro Atoll. Names on other charts are listed to support the above accusations.

Table II

Names of Islets on Nukuoro Atoll

	Names at Present	Sheet 5133 1 BE AMS Series W856	U.S. Navy H.O. Chart 6042	Deutsche Admiralitätskarte 97 (corrected to 1911)	Map of the Survey Ship "Orion" (#91)
1.	Moduilalo	--	--	--	--
2.	Olomanga	Oromange	Oromange	Oromange	--
3.	Deahua	Deahua (Teahua)	Deahna	Deahua	--
4.	Moduilodo	Motuiloto	Motu Lloto	Motuiloto	--
5.	Gausema	Kaujema	Kaujema	Kaujema	--
6.	Senugudai	Shenukdei	Shenukdei	Schenukdai	Schenukdei
7.	Masalu	Masopa (Mohiringatua)	--	--	Masops
8.	Masagumani-inage	Masakomani	--	--	Masakomani
9.	NUKUORO	NUKUORO	NUKUORO	NUKUORO	NUKUORO
10.	Dagamanga	Takonrau	Takonrau	Takonran	Takonrau
11.	Ladi	Rati	--	--	Lati
12.	Demodu	Heisisi	--	--	Timotu
13.	Haisisi	Te Motu	--	--	Heisisi
14.	Ngaligi	Pelhau	--	--	Bakau
15.	Sungaulohu	Shugnaurohu	Shugnaurohu	Schugnaurohu	Schugnauroho
16.	Tuila	Tuila	Tuila	Tuila	Tuila
17.	Haduganae	Hatu kanei	--	--	Hatu kanei
18.	Balaiasi	Pala i iasi	--	--	Paleyasi
19.	Moduovega	Moduoveka	--	--	Motuowega
20.	Baonga	Paonga	--	--	Boumga
21.	Ahuloloa	Ahuroroa	Ahuroroa	Ahuirorca	Ahu roroa
22.	Moduodula	Moduotura	--	--	Motuotura
23.	Ahuedolu	Ahuwetoru	--	--	Ahuwetoru
24.	Moduovae	Motuwei	Motu Wei	Matuwei	Motuwei

Table II (cont.)

	Names at Present	Sheet 5133 1 BE AMS Series W856	U.S. Navy H.O. Chart 6042	Deutsche Admiralitätskarte 97 (corrected to 1911)	Map of the Survey Ship "Orion" (#91)
25.	Deahu*	Teahu (Teachua)	--	--	Deahu hatinga
26.	Deahu*	--	--	--	Deahu wihinger
27.	Deahu*	Tehu (Teachua)	--	--	Deahu
28.	Sabinimadogo	Sapinimatok	Sapinimatok	Sapini matok	Sapini Matok
29.	Modubodai	Motuitua	Motu Ituo	--	Mot Bodei
30.	Moduidua	Tahangaroro	Tahangolo	Motuituo	Motuitua
31.	Ahuilodo	Ahuiroto	--	Tahanga roro	Tahanga roo
32.	Dahangahaino	Motupotai	Tahangatabu	--	Ahuilodo
33.	Dahaugadabu	Tahangatabu	--	Tahanga tabu	Tahanga tabu
34.	Ahulegalega	Ahu Legalega	--	--	Ahuregatik
35.	Masagumani-ilalo	Masaku Mani	--	--	Masako mani tara
36.	Niulegida	Niurekita	--	--	Arakanui
37.	Ahulanui	Alukanui	Alukanui	Arukanui	--
38.	Dolungahale	Tolu na hale	--	--	Terung hari
39.	Dalagivao	Motunui	Motonui	--	Taraki wahu
40.	Moduia	Tarakaivao	--	--	Motu ia
41.	Modunui	Motoia	--	Motoma	Motonui
42.	Namoilodoa	Namuirotoa	Namuirotoa	Namui rotoa	Namui rotoa
43.	Hauosiga	Hau Usiki	--	--	Ahuosi kat
44.	Gabinivele	Kapinivere	Kapinivere	Kapini vere	Kapini vere
45.	Dalainamu	Tavainamu	--	--	Tarei namu
46.	Deungagelegele	Tonga Kerikeri	Tonga Kerikeri	Tonga kerikeri	Tonga kerikeri

* These islands, collectively called Denga Ahu, are locally distinguished from each other, when necessary, by adding the name of the present owner. Since this stipulation changes the name in every generation, cartographers are advised to use only the name listed.

ATOLL RESEARCH BULLETIN

No. 108

Atoll News and Comment

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Atoll News and Comment

To keep our readers informed on current happenings of interest to students of coral atolls and reefs we offer another of this series. We will continue to welcome short items of current interest, or comments on overlooked or underemphasized past works, from any source.

Atoll Investigations

Displaced island communities:

Prof. Homer G. Barnett, of the Dept. of Anthropology, University of Oregon, has sent us the description of a five year project being undertaken by his department to make a comparative study of cultural change and stability in displaced communities in the Pacific Islands. This study will be primarily a historical study and will concentrate mainly on social effects, rather than the influences of the physical environment. "The project is conceived to be a study of cultural change within the context of an evolving continuum of community life." It is of particular interest to us because of the ten transplanted communities selected for study, five are atoll peoples. These are as follows:

"1962-63. Field Director, H.G. Barnett
1. Gilbertese relocated on Gizo Island in the Solomon Islands.
2. Ellice Islanders relocated on Kioa Island near Vanua Levu in the Fiji Islands.

1963-64. Field Director, Leonard Mason.
3. Bikini Islanders relocated on Kili Island, both in the Marshall Islands.
4. Eniwetok Islanders relocated on Ujelang atoll, both in the Marshall Islands.

1964-65. Field Directors, James Spillius and H. E. Maude.
5. Tikopians emigrated to Russell Island in the Solomon Islands.
6. Gilbertese relocated on Gardner Island in the Phoenix Islands."

with regard to item no. 6, however, see ARB 100, p. 3.

Central Pacific Ocean Area:

The Pacific Ocean Biological Survey Program is being conducted by the Division of Birds, Smithsonian Institution, to satisfy a need for information on migration, distribution, and ecology of birds and terrestrial vertebrates, and their ectoparasites, in the Central Pacific Ocean Area (Hawaiian Leewards, Phoenix and Line Islands). Objectives will be achieved by carrying out a series of at-sea observations and field studies on selected islands. The project began in October 1962 and will run through December 1965.

A first product of this investigation is a report entitled "Preliminary biological survey of Sand Island, Johnston Atoll", 1-136, Washington, 1964.

Line Islands:

Christmas Island: Dr. Philip Helfrich, of the University of Hawaii writes, Oct. 23, 1963, as follows: "This past summer we spent some time on Christmas Island with Dr. William Gilbert of Albion College, Michigan. He aided us in an ecological study of the Cochrane Reef area and in addition, we collected numerous samples of the gelatinous algae that line many of the lakes. We also recorded the temperature and took salinity samples from 13 of these lakes. On many of the maps these lakes, particularly those in the southeast portion of Christmas Island, are marked "fresh water lakes." It is of interest that the salinity of these lakes ranged from 33.03 to 302.27 parts per thousand! I want to do some further elemental analyses of these samples and plan to report them in a note in the Atoll Research Bulletin." He was able, through the courtesy of the RAF, to photograph the study area, as well as other parts of the island from the air. It would be of great interest if these photos could be compared with those taken in 1936 of the atoll by photographers on HMS Achilles if these can be located. He also writes that Philip Ashmole is now carrying on the bird studies, originally planned then dropped (see ARB 84, 94).

Fanning Island: According to a report in Nature 200: 325-326, 1963, an expedition under University of Hawaii sponsorship made studies of certain invertebrate groups and their ecology on Fanning Island, between June 22 and Aug. 24, 1963.

Caroline Islands:

Nukuoro: Mr. Vern Carroll has returned from his expedition to Nukuoro (see ARB 100, p. 4) for the summer. Some of the preliminary results are presented earlier in this issue. He intends to return to the atoll for another extended period beginning this fall.

Indian Ocean:

Maldives: A small party, under the leadership of our correspondent, Dr. David R. Stoddard, of the Geography School, Cambridge University, is working on Gan, Addu Atoll, this summer, investigating sedimentation, wave and tide relationships, and beachrock occurrence and formation. The other members of the party are Dr. Peter Spencer Davies, ecologist from the University of Glasgow, Andrew Keith, geography student from Cambridge, and David [illegible], botany student, also from Cambridge. Recent political disturbances in the Maldives have unfortunately restricted the activities of the expedition to the immediate vicinity of Gan islet and the lagoon, but we hope to be able to report significant accomplishments in a future issue.

West Indies:

Bahamas: Mr. John D. Milliman, of the Institute of Marine Science, University of Miami, is carrying on an investigation this summer on the marine geomorphology and hydrography of Hogsty Reef and Little Inagua Island, in the southeastern Bahamas.

Publications

Three recent reports that have come in are of particular interest to students of reef ecology. Dr. Tom Goreau has presented a detailed discussion of his work on "Calcium carbonate deposition by coralline algae and corals in relation to their roles as reef-builders" (Ann. N. Y. Acad. Sci. 109: 127-167, 1963) in which he describes in detail his methods, gives careful attention to rates of calcification, to the effects of light, the relation between calcification and photosynthesis in both algae and corals, and emphasizes this relation as a factor governing population composition and growth form of the hermatypic biota in the reef. Dr. Goreau and Dr. Willard F. Hartman have treated in detail "Boring sponges as controlling factors in the formation and maintenance of coral reefs" (Amer. Assoc. Adv. Sci. pub. 75: 25-54, 1963). They summarize what is known, and not known, of the mechanism of boring by clionid sponges, and survey their occurrence and erosional effects at different depths on the reefs on the north coast of Jamaica. This is one of the first papers treating in any detail the erosion that takes place on the parts of the reefs below effective wave action. J. E. Hoffmeister and H. G. Multer, in "Growth-rate estimates of a Pleistocene coral reef of Florida" (G.S.A. Bull. 75: 353-358, 1964) have used an interesting combination of experimental and observational data to arrive at estimates of the time required for the formation of a reef. The wide difference in estimates depending on the assumptions used indicates that there is not yet any very firm means of determining reef growth rates. This attempt is better than most in that it takes more of the possibilities of variation into account.

Pacific Basin Biogeography:

Students of Pacific atolls will welcome the publication of a volume of symposia on "Pacific Basin Biogeography", edited by J. Linsley Gressitt, published by the Bishop Museum Press, Honolulu (1963), $12. Three of these symposia, treating the North Pacific (Bering Arc), Tropical Pacific, and South Pacific (Antarctic) relationships, respectively, present a comprehensive picture of what is presently known of the distributional patterns of Pacific plants and animals, projected against a background of geology and paleogeography. There is enough speculation, some of it quite unbridled, to make interesting reading. The fourth symposium is on "Modification of biotic balance of island faunas and floras". In several papers it presents some of the effects of man's presence on islands. The volume contains much of interest to all biogeographers and ecologists with any interest in islands.

Carnival Under the Sea:

Dr. René Catala is known to many ARB readers because of his fine research aquarium in Noumea, where one may study corals and many other reef organisms in comfort without even getting wet. Some may have seen his magnificent movies of undersea animals and featuring the beautiful fluorescence of corals, discovered by Dr. Catala. Now, for the stay-at-homes who cannot go to New Caledonia and see these marvels at first hand in the aquarium, Dr. Catala has written a book, mainly consisting of color plates of the inhabitants of his aquarium. This will be published this fall, in both English and French editions, by Editions Sicard, Paris. The English title is "Carnival under the sea", the French, "Carnaval sous la mer". A subscription announcement, with a sample plate, has been sent to all recipients of ARB. A few are still available from the ARB editors.

Coral Reef Biology:

Yonge, C. M., The biology of coral reefs, in: F. S. Russell, ed., Advances in Marine Biology, 1: 209-260, 1963.

In all active scientific fields, and more especially in such a period as the present with an enormous yearly volume of published work, frequent reviews are necessary to enable specialists to keep themselves oriented in their fields and in relation to science as a whole. When these reviews can be written by the acknowledged masters of the fields it is a great advantage. Such is that on coral reef biology by the dean of the workers on this subject, C. M. Yonge. This article is so well-conceived, and the material so well-selected, that it should be required reading for anyone interested in any aspect of coral reef geology or ecology. The author summarizes the systematics and distribution of the corals, then relates the origin of coral colonies by the settlement of planulae to some of the confusing difference in growth-form that complicates the classification. Then he summarizes, perhaps less adequately than in other sections, the ecology of atolls. The Atlantic reefs are given special treatment, comparing them with Pacific ones. A short summary of the erosional processes on reefs follows. A short section on physiology leads to a major treatment of the problem of zooxanthellae and their relation to the physiology of the coral animals, and even to the rate of skeletal formation. Interesting is the fact that zooxanthellae now seem to have turned out to be vegetative stages of planktonic dinoflagellates. Growth and the effect of light are treated. Finally, and of great importance in the ecology of reefs and atolls, the author summarizes what is known, and claimed, of productivity on coral reefs. Investigation of this aspect of coral reef ecology seems really only at its beginning. The six page bibliography is extremely valuable.

Heron Island, Capricorn Group:

Coral Cay vegetation, Heron Island, Great Barrier Reef, by Mary E. Gillham (Proc. R. Soc. Queensland 73: 79-92, 1963), is a very detailed account of the vegetation of the island briefly described in ARB 82,

and its environment, with an essay toward interpretation of successional trends and environmental relationships. A tabular list of species and a sketch map are included. The list includes five species not included in ARB 82, as follows:

Hibbertia sp.
A seedling of Cucumis vulgaris?
Vitex ovata
Achyranthes aspera
Poa annua.

Included are two species of Pandanus, both of which are considered by Fosberg and Thorne to be forms of P. tectorius, sensu lato. We do not know what Cucumis vulgaris is.

The Fosberg and Thorne list includes 38 species not in the Gilham list. Of these, 30 are pot plants or obviously planted, 6 are widespread weeds, and 2, Commicarpa chinensis and Sophora tomentosa are normal members of the strand flora.

Eniwetok Atoll:

We recently received an undated report entitled "A review of the ecology of Eniwetok Atoll, Pacific Ocean", by A. M. Woodbury, of the University of Utah. This brings together a good deal of information, not all of it pertaining to Eniwetok—e.g. a discussion of an epidemic among seals in Antarctica, and a list of medically important arthropods of Ponape. The vegetation is treated very casually, indeed, and the soils even more so. The section on birds is by far the most detailed, but even this is marred by careless errors and failure to distinguish between observations that apply to Eniwetok and those made of the same species elsewhere. Flagrant examples of this are the lists of bird parasites, which were taken from a publication on parasites of North American birds. However, if the report is read with these peculiarities in mind, it is a good source for general information on the land biology of the atoll.

Matters of General Interest

Lt. Col. R. B. Seymour Sewell:

Col. Seymour Sewell died in Cambridge on 11 February 1964, aged 83. Before the Second World War he had made major contributions to reef studies in the Indian Ocean, before retiring, in 1935, to Professor Stanley Gardiner's Department of Zoology at Cambridge. Gardiner and Sewell between them are responsible for the greater part of our knowledge of the Indian Ocean reefs, particularly those of the Maldive Islands. Sewell's early training was in zoology and medicine, and he began his professional career in the Indian Medical Service in 1908. In 1910 his appointment as Surgeon-Naturalist to the Marine Survey of India led to growing interest in the Indian seas, particularly on the Burma coast and the Nicobar Islands, and then in the Maldives. His 1935 paper on "Coral and coral formations in Indian waters" remains a classic of reef literature. Before

it appeared he was appointed leader of the British Museum's John Murray Expedition of 1933-4, which in addition to the collection of geophysical and systematic data led to Sewell's own accounts of Addu and Goifurfehendu atolls, Maldive Islands, which still have few counterparts in the Indian Ocean reef literature.

Sewell was primarily a marine zoologist, and his major interest in the systematics of the copepoda is reflected in his fifty or so published papers. In his reef work he was influenced by Daly's and Gardiner's emphasis on recent negative shifts of the sea, which he attempted to synthesise and explain in 1928. He was not a trained geologist or physiographer, but rather, as his official title implied, a naturalist, with correspondingly wide interests; yet his reef work is full of acute observations on physiography and sedimentation. For the last few years he was immobilised in Cambridge by paralysis, but remained mentally sprightly, and indeed, within a few weeks of his death he was still working on data from the John Murray Expedition. Among other honours, he was President of the Ray Society (1950-53) and of the Linnaean Society of London (1952-55), and a Fellow of the Royal Society. Few specialists nowadays can hope to have the breadth of competence and accomplishment that Seymour Sewell had. His main reef papers were:

1928. A study of the recent changes of sea level based largely on the study of coral growth in Indian and Pacific seas. Internat. Rev. der Ges. Hydrobiol. und Hydrogr. 20, 89-102.

1932. The coral coasts of India. Geographical Journal, 79, 449-465.

1935. Studies on coral and coral formations in Indian waters. Mem. Roy. Bengal, 9, 461-540.

1936. An account of Addu atoll. Scientific Reports, John Murray Expedition 1933-4, 1, 63-93.

1936. An account of Horsburgh or Goifurfehendu atoll. Scientific Reports, John Murray Expedition 1933-4, 1, 109-125.

D. R. Stoddart

Heron Island Laboratory:

We had a recent brief visit from Prof. W. Stephenson, of the Zoology Dept., University of Queensland, who has been spending a year teaching in this country. He informs us that the Heron Island Laboratory now has five buildings completed, thus improving the already comfortable facilities for research at the south end of the Great Barrier Reef. Visitors from abroad are welcome and are encouraged to make use of this station (see ARB 62, 99). Prof. Stephenson is continuing his researches on the fauna inhabiting beach-rock.

Resolution on Leeward Islands:

At a recent meeting, the Hawaiian Academy of Science Council voted to refer a resolution, urging that control of the Leeward Islands

as a bird and wildlife refuge be retained by the Federal Government, to the membership. The text of the resolution is as follows:

"The Leeward Islands, a part of the Hawaiian chain which extends for about 1300 miles toward the northwest from Kauai, consists of several reefs and shoals, and of 9 islands and atolls: Nihoa, Necker, French Frigate Shoal, Gardner Pinnacles, Laysan, Lisianski, Pearl and Hermes Reef, Midway, and Kure. All of these islands, except Midway, became part of the Territory of Hawaii at the time of annexation. During the early part of this century, feather hunters decimated the bird populations on several of the islands, and on February 3, 1909, all except Midway and Kure were placed in the Hawaiian Islands Bird Reservation by Executive order of President Theodore Roosevelt. Kure was added to the reservation in April, 1909. Midway has never been a part of the Reservation.

The area set aside as the Hawaiian Islands Bird Reservation is today known as the Hawaiian Islands National Wildlife Refuge. Politically, these islands are a part of the State of Hawaii and of the City and County of Honolulu. The Refuge is in Federal ownership under the jurisdiction of the Bureau of Sport Fisheries and Wildlife, U.S. Fish and Wildlife Service, Department of the Interior. In accordance with an agreement between the State of Hawaii and the Dept. of the Interior, immediate administration is under the Director, Division of Fish and Game, Dept. of Land and Natural Resources, State of Hawaii. The funds for administration of the Refuge are given the State by the Dept. of Interior.

Recently, there has been a proposal that the Department of the Interior turn over ownership and control of the Leeward Islands to the State of Hawaii. In response to this proposal, the following resolution will be presented to the academy membership:

"WHEREAS the islands composing the Hawaiian Islands National Wildlife Refuge provide nesting sites for several species of sea birds, and in some instances are the major breeding sites of the species; and

"WHEREAS on these islands are found three species of birds, the Laysan duck, the Laysan finch, and the Nihoa millerbird, which occur nowhere else in the world; and

"WHEREAS these islands provide a refuge for the Hawaiian monk seal; and

"WHEREAS on these islands are found several species of plants which occur nowhere else in the world;

"THEREFORE the greatest scientific value of these islands lies in their continued use as a Wildlife Refuge; and

"THEREFORE, BE IT RESOLVED that the Hawaiian Academy of Science, at its annual business meeting on April 23, 1964, urges that the control of the Hawaiian Islands National Wildlife Refuge remain vested in the United States Department of the Interior;

"BE IT FURTHER RESOLVED that copies of this resolution be sent to the Secretary of the Interior, the Director of the U. S. Fish and Wildlife Service, the Governor of Hawaii, the Director of the State Department of Land and Natural Resources, and the Director of the State Division of Fish and Game."

In this connection see ARB 84, 94, 97, 98, 103, and a recent article by J. W. Aldrich, "The Gooney birds of Midway" (Nat. Geogr. Mag. 125: 839-851, June 1964). The killing of the albatrosses being carried out on Midway Island makes it even more imperative to preserve the habitats of the few of these birds that inhabit neighboring islands. We would have suggested that the resolution also protest the desecration of this wildlife refuge by the U. S. Coast Guard (see ARB 51, 78, 79, 94, 103) which seems to be exempt from the Fish and Wildlife Service regulations.